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CONTENTS

Section	Page
2.1.4.3 Actuators	2-13
2.1.4.4 PCS Operation	2-14
2.1.5 Electrical Power Subsystem	2-14
2.1.5.1 Solar Arrays	2-14
2.1.5.2 Batteries and Charge Current Controllers	2-14
2.1.5.3 Power Control and Distribution Units	2-15
2.1.6 Thermal Control	2-16
2.1.7 Safing (Contingency) System	2-16
2.1.7.1 PSEA and RMGA	2-18
2.2 The Optical Telescope Assembly	2-19
2.2.1 Primary Mirror Assembly	2-20
2.2.1.1 Primary Mirror	2-20
2.2.1.2 Main Ring	2-21
2.2.1.3 Reaction Plate	2-22
2.2.1.4 Baffles	2-23
2.2.2 Secondary Mirror Assembly	2-23
2.2.3 Focal Plane Structure Assembly	2-25
2.2.4 OTA Equipment Section	2-26
2.3 Fine Guidance Sensors	2-26
2.3.1 FGS Composition and Function	2-27
2.3.2 Wavefront Sensor	2-28
2.4 Solar Arrays	2-29
2.4.1 Configuration	2-29
2.4.2 Solar Array Subsystems	2-29
2.4.3 Operation	2-30
2.5 Scientific Instrument Control and Data Handling Unit	2-30
2.5.1 SI C&DH Components	2-31
2.5.1.1 NASA Computer	2-31
2.5.1.2 STINT Unit	2-31
2.5.1.3 Control Unit/Science Data Formatter	2-31
2.5.1.4 Power Control Unit	2-32
2.5.1.5 Remote Module Units	2-32
2.5.1.6 Communications Buses	2-32
2.5.2 Operation	2-32
2.5.2.1 System Monitoring	2-32
2.5.2.2 Command Processing	2-32
2.5.2.3 Science Data Processing	2-32
2.6 Space Support Equipment	2-33
2.6.1 Flight Support Structure	2-34

Section		Page

Section		Page

Section **Page**

ILLUSTRATIONS

TABLES

Section 1
INTRODUCTION

When Galileo peered through his small telescope nearly 400 years ago, it resulted in an unprecedented period of astronomical discovery. When NASA's Hubble Space Telescope (HST) is placed into orbit to begin its observations of the heavens, it will usher in a period of discovery expected to be as astounding and productive as the introduction of the first telescope.

Ground-based astronomy has always been hampered because observations must be made through the earth's turbulent, particle-filled atmosphere, which absorbs and distorts incoming starlight and severely limits astronomical observations. Placing the Hubble Space Telescope in a 330-nmi (607-km) orbit, above all but the thinnest remnants of atmosphere, will give astronomers an open window to the universe. The Space Telescope will be able to detect an object of a particular brightness that is five times farther out in space than an object of the same brightness that can be seen by ground telescopes. The HST will detect objects 25 times fainter than the dimmest objects seen from earth. The Space Telescope will provide astronomers with an observable universe 250 times larger than currently visible, making the farthest reaches of the universe, perhaps as far away as 14 billion light years[1], available for study.

The Space Telescope will view galaxies, stars, planets, comets, possibly other solar systems, and even unusual phenomena such as quasi-stellar objects (quasars), with 10 times the clarity (or fineness of detail) of earth telescopes. The HST will be able to separate stellar objects that seem indistinguishable because they are so close in the visible sky, only one-tenth arcsecond apart (an arcsecond is a slender wedge of angle, 1/3600th of one degree, in the 360-degree "pie" that makes up the sky). A distant galaxy, just a faint dot of light seen from the surface of the earth, will be resolved into a multitude of stars. Planets as far away as Saturn will be seen with the same clarity obtained by recent NASA satellite fly-by missions and will be studied over much longer time periods.

The Hubble Space Telescope is the product of a partnership between NASA, the European Space Agency, contractors, and the international community of astronomers. It is named after Edwin P. Hubble, an American astronomer who discovered the expanding nature of the universe and was the first to realize the true nature of galaxies. He derived Hubble's Law, which relates a galaxy's distance to how fast it recedes from us. His work became a major basis for the "Big Bang" theory of the beginning of the universe. (The Hubble Law is discussed in more detail in Appendix A, "Astronomical Concepts.")

The Space Telescope is designed as the first long-term, maintainable, and repairable space observatory. It will detect starlight that has traveled for billion of years, since distance (light-years) is calculated as the time it takes light to move between points in space. The universe is estimated to be 15 to 20 billion years old, so the HST will see events and phenomena that occurred close to the beginning of the current expansion phase following the Big Bang. Astronomers can study the development of stars, the composition of galaxies, and the effect of interstellar clouds on light for answers to questions about the beginning and the future of the universe. Of particular interest will be quasars, black holes, exploding galaxies, and other unusual phenomena.

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[1] Astronomical terms and concepts, such as "light years", are explained in Appendix A, "Astronomical Concepts."

1.1 HUBBLE SPACE TELESCOPE CONFIGURATION

The major elements of the HST are the Optical Telescope Assembly (OTA), the five Scientific Instruments (SIs), and a Support System Module (SSM) structure that houses electronic and mechanical support systems, the telescope, and the SIs. Figure 1-1 illustrates the overall HST configuration, and Table 1-1 gives the specifications for the Hubble Space Telescope and its scientific instruments.

1.1.1 Support Systems Module

The Support Systems Module encloses the OTA and the five SIs. Like the dome of an earth-based observatory, the SSM contains all the structures, electronics, and power subsystems to operate the Hubble Space Telescope.

The overall spacecraft is 42.5 ft (13 m) long and weighs 25,500 lb (11,600 kg). On the outside are four antennas for communications, two solar array panels that collect energy for the HST, and storage bays for electronic gear.

The SSM consists of the front-end light shield, with an aperture door that opens to admit light. The shield connects to the forward shell. The solar arrays and high-gain antennas are mounted on the forward shell. The arrays, 40 feet long, provide electrical energy (from sunlight) to charge the spacecraft batteries which, in turn, power the HST. The antennas send and receive information.

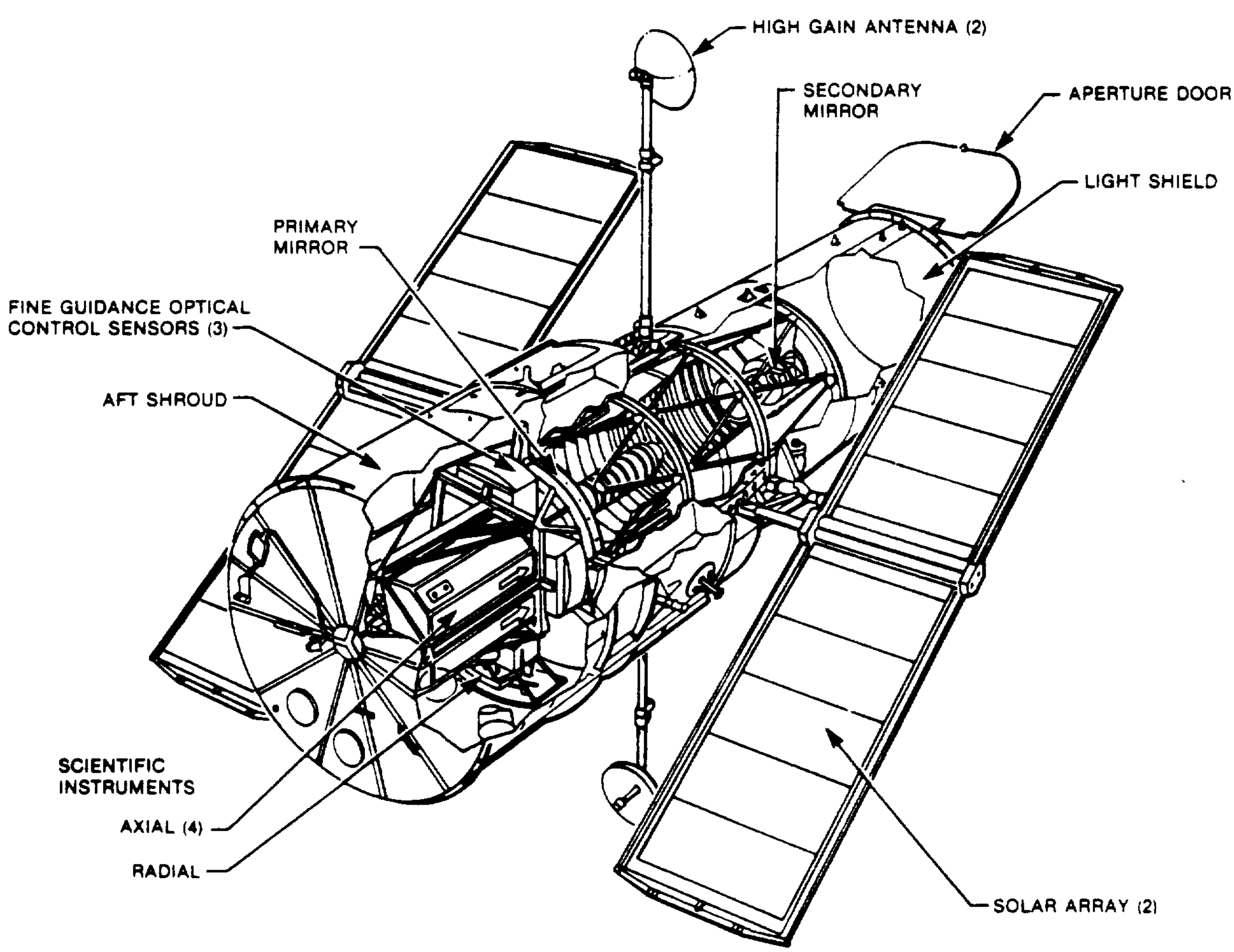


Figure 1-1 Overall HST Configuration

Table 1-1 HST, Scientific Instrument Specifications

HUBBLE SPACE TELESCOPE	
Weight	25,500 lb (11,600 kg)
Length	42.5 ft (13 m)
Diameter	14 ft (4.2 m) at widest
Optical System	Ritchey-Chretien design Cassegrain telescope
Optical Length	189 ft (57.6 m) folded to 21 ft (6.4 m)
Primary Mirror	94.5 in. (2.4 m) in diameter
Secondary Mirror	12.2 in. (0.3 m) in diameter
Field of View	See instruments/sensors
Pointing Accuracy	0.007 arcsec for 24 hr
Magnitude Range	5 mv to 29 mv
Wavelength Range	1100 to 11,000 Angstroms
Angular Resolution	0.1 arcsec at 6328 Ang.
Orbit	330 nmi (607 km), inclined 28.5° from equator
Orbit Time	94 minutes per orbit
Mission	15 years

FAINT-OBJECT CAMERA		WIDE FIELD/PLANETARY CAMERA	
Weight	700 lb (318 kg)	Weight	595 lb (270 kg)
Dimensions	1	Dimensions	2
Principal Investigator	F.D. Macchetto, Eur. Space Agny	Principal Investigator	J.A. Westphal, CIT
Contractor	ESA (Dornier, Matra Corp.)	Contractor	Jet Propulsion Laboratory
Optical Modes	f/96 f/48	Optical Modes	f/12.9 (WF), f/30 (P)
Field of View	11.2, 22 arcsec ^{2}	Field of View	160, 66 arcsec ^{2}
Magnitude Range	5-28 m_v	Magnitude Range	9-28 m_v
Wavelength Range	1150-6500 Ang.	Wavelength Range	1150-11,000 Ang.

GODDARD HIGH-RESOLUTION SPECTROGRAPH		FAINT-OBJECT SPECTROGRAPH	
Weight	700 lb (318 kg)	Weight	680 lb (309 kg)
Dimensions	1	Dimensions	1
Principal Investigator	J.C. Brandt, NASA/GSFC	Principal Investigator	R.J. Harms, ARC
Contractor	Ball Aerospace	ContractoR	Martin Marietta
Apertures	2 arcsec ^{2} target, 0.25 arcsec ^{2} science	Apertures	0.1-4.3 arcsec ^{2}
Resolution	2000-100,000	Resolution	250; 1300
Magnitude Range	17-11 m_v	Magnitude Range	19-26 m_v
Wavelength Range	1050-3200 Ang.	Wavelength Range	1100-8000 Ang.

HIGH-SPEED PHOTOMETER		FINE GUIDANCE SENSORS	
Weight	600 lb (273 kg)	Weight	485 lb (220 kg)
Dimensions	1	Dimensions	3
Principal Investigator	R. Bless, U. of Wisconsin	Contractor	Perkin-Elmer Corp.
Contractor	U. of Wisconsin	Astrometric Modes	Stationary & Moving Target, Scan
Apertures	0.4,1.0,10.0 arcsec ^{2}	Precision	0.002 arcsec ^{2}
Resolution	Filter-defined	Measurement Speed	10 stars in 10 min
Magnitude Range	< 24 m_v	Field of View	Access: 60 arcmin ^{2} Detect: 5 arcsec ^{2}
Wavelength Range	1200-7500 Ang.	Magnitude Range	4-18.5 m_v
		Wavelength Range	4670-7000 Ang.

1 Dimension = 3x3x7 ft (0.9x0.9x2.2 m)
2 Dimension = Camera - 3.3x5x1.7 ft (1x1.3x0.5 m)
Radiator - 2.6x7 ft (0.8x2.2 m)
3 Dimension = 1.6x3.3x5.4 ft (0.5x1x1.6 m)

Next is the equipment section, a ring of bays that house power, computer, and communication equipment. At the rear, the aft shroud contains the scientific instruments.

The light shield and forward shell are 10 ft (3.1 m) in diameter; the equipment section and aft shroud are 14 ft (4.3 m) in diameter.

1.1.2 Optical Telescope Assembly

The Optical Telescope Assembly consists of two mirrors, support trusses, and the focal plane structure. The incoming light travels down a tubular baffle that absorbs stray light. The light is reflected by a 94.5-in. (2.4 m) primary mirror and then travels to a secondary mirror, 12.2 in. (0.3 m) in diameter. Then the light is reflected by the secondary mirror through a hole in the primary mirror, to the focal plane, which is aft of the primary mirror. Here the scientific instruments and fine guidance sensors receive the light. The optical system is a Cassegrain design, which means the telescope's focal length is "folded" into a smaller physical length, with a variation, called Ritchey-Chretien, that makes the mirrors hyperbolic to reduce aberrations in the image plane.

1.1.3 The Scientific Instruments

The first complement of instruments consists of two cameras, two spectrographs, and a photometer. The guidance sensors can also act as science instruments by measuring star locations precisely. Four of the instruments are housed in a focal plane structure aligned with the main optical axis, behind the primary mirror. One instrument and the three guidance sensors are mounted radially (perpendicular to the others). See Figure 1-2 for the scientific instruments.

The Faint Object Camera (FOC), the Faint-Object Spectrograph (FOS), the Goddard High-Resolution Spectrograph (GHRS), and the High-Speed Photometer (HSP) are rectangular boxes 3 x 3 x 7 ft (0.9 x 0.9 x 2.2 m); the Wide Field/Planetary Camera (WF/PC) is 3.3 x 5 x 1.7 ft (1 x 1.3 x 0.5 m).

The WF/PC and the FOC have similar functions but concentrate on different types of objects. The WF/PC splits the light image into quarters, using a four-sided pyramid mirror, then focuses each quadrant onto one of two sets of four sensors. The sensors are charge-coupled detectors (CCDs) and function as the electronic equivalent of extremely sensitive photographic plates. The WF/PC operates in two modes:

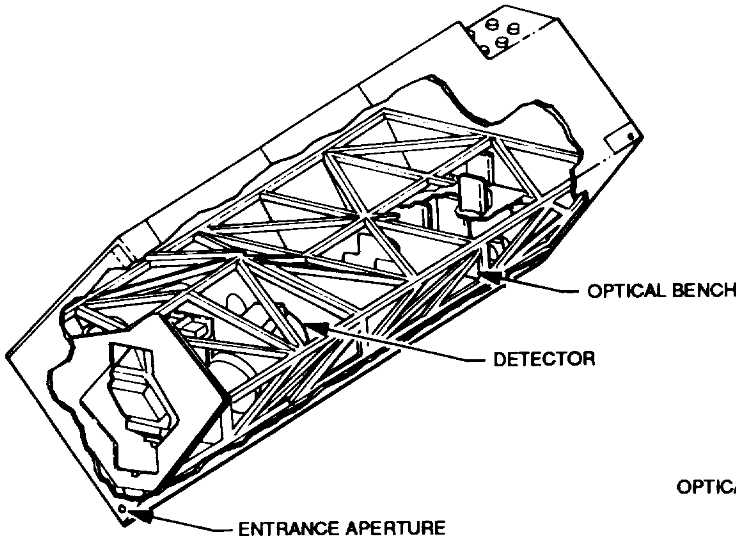
1. Wide-Field mode, which will view 7.2 arc-min^2 sections of the sky, and
2. Planetary mode, which will look at narrower fields of view, such as planets or areas within other galaxies.

The CCDs record the incoming light, and the information is transmitted to earth as electronic signals and reformed into images.

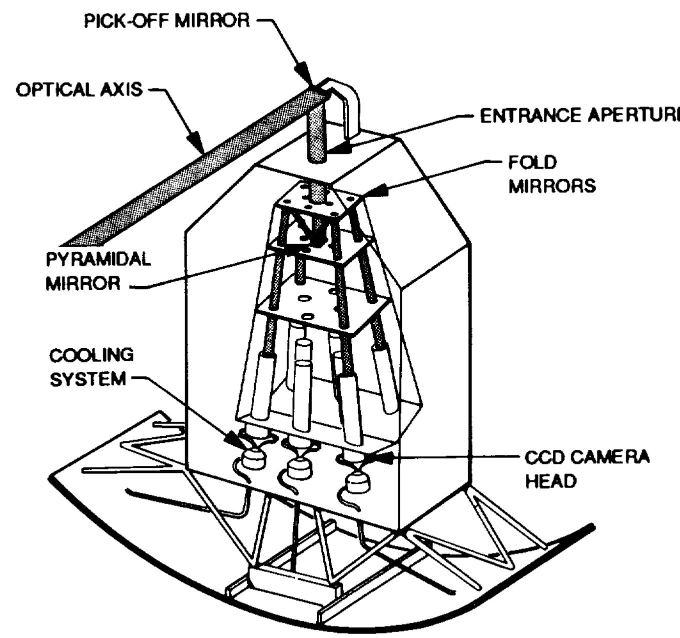
The FOC reflects light down one of two optical pathways. The light, after passing through filters or through devices that can block out light from bright objects to see background images, enters a detector. The detector intensifies the image, then records it much like a television camera. For faint objects, images can be built up over long exposure times. The total image is translated into digital data, transmitted to earth, and then reconstructed.

Spectrographs separate the incoming light into its component wavelengths, revealing information about the atomic composition of the light source. The Hubble Space Telescope's two spectrographs can detect a broader range of wavelengths than is possible from earth because there is no atmosphere to absorb certain wavelengths. Scientists can determine the chemical composition, temperature, pressure, and turbulence of the stellar atmosphere producing the light, all from spectral data.

GODDARD HIGH RESOLUTION SPECTROGRAPH



WIDE FIELD/PLANETARY CAMERA



FAINT OBJECT CAMERA

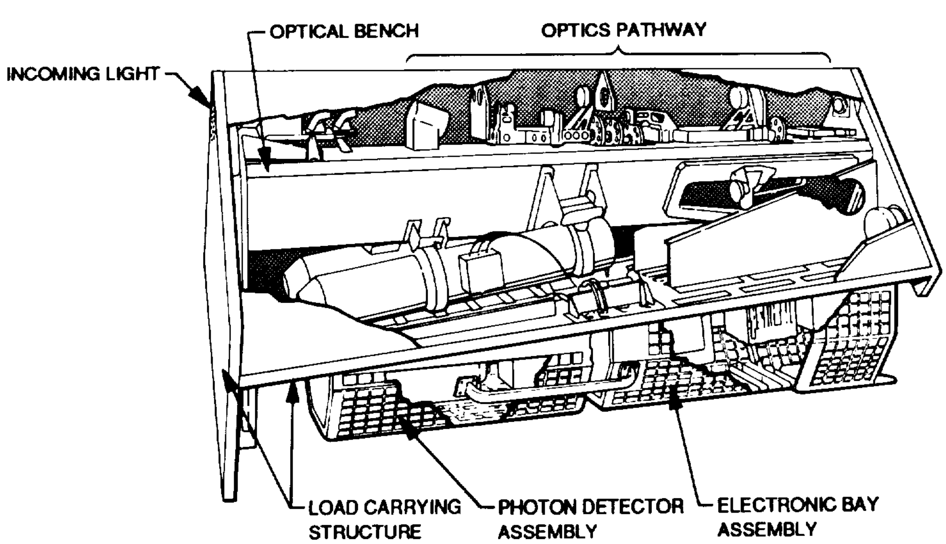
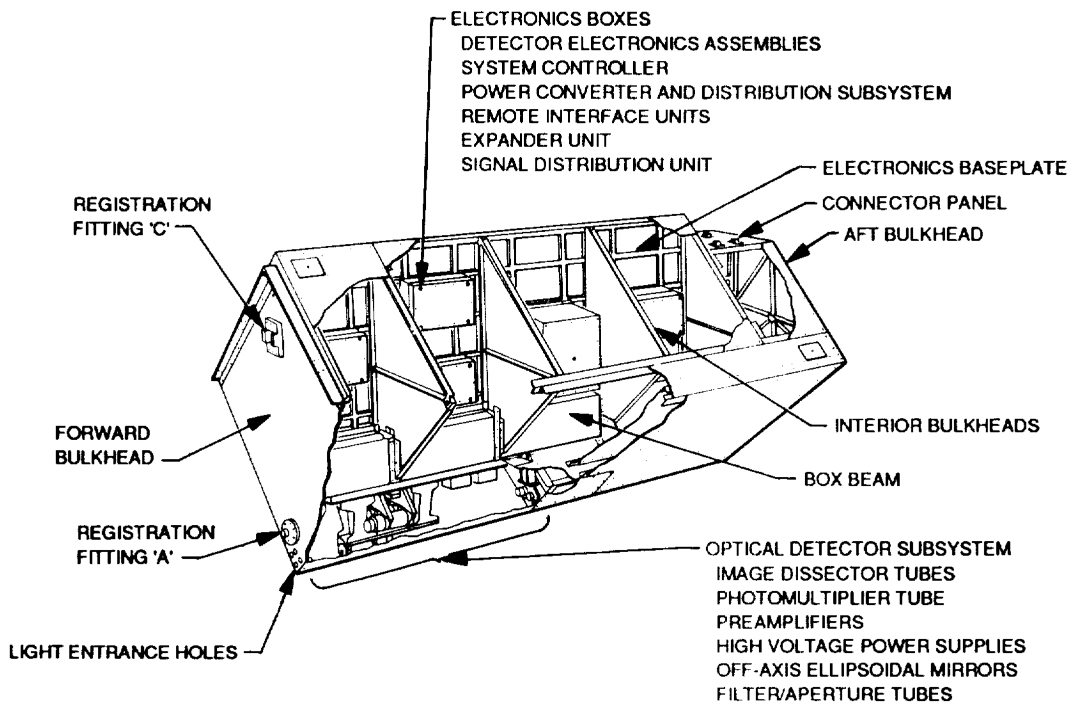


Figure 1-2 The Scientific Instruments (Page 1 of 2)

HIGH SPEED PHOTOMETER



FAINT OBJECT SPECTROGRAPH

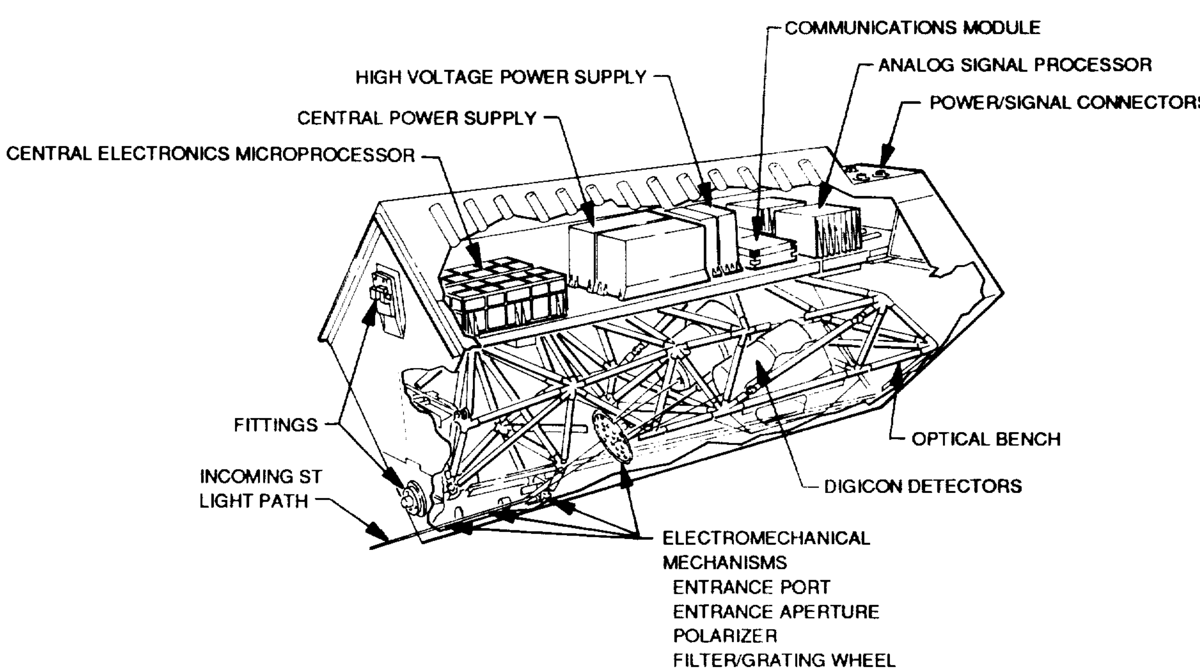


Figure 1-2 The Scientific Instruments (Page 2 of 2)

The FOS can detect detail in very faint objects, such as those at great distances. The GHRS can detect fine detail in the light from somewhat brighter objects. The FOS can detect light ranging from ultraviolet to red spectral bands; the GHRS detects only ultraviolet light.

Both spectrographs operate in essentially the same way. The incoming light passes through a small entrance aperture, then passes through filters and diffraction gratings, which work like prisms. The filter or grating used determines what range of wavelength will be examined and in what detail. Then the spectrograph detectors record the strength of each wavelength band and send it back to earth.

The fifth scientific instrument is the HSP. It measures the intensity of starlight (brightness), which will help determine astronomical distances. Its principal use will be to measure extremely-rapid variations or pulses in light from celestial objects, such as pulsating stars.

The HSP will produce precise brightness readings. Light passes into one of four special signal-multiplying tubes that record the data. The HSP can measure energy fluctuations from objects that pulsate as rapidly as once every 10 microseconds. From HSP data, astronomers expect to learn much about such mysterious objects as pulsars, black holes, and quasars.

The three fine guidance sensors are part of the spacecraft's pointing system. Two sensors lock onto a stellar target. The third can measure the brightness and relative position of stars. These measurements, referred to as astrometry, will increase the accuracy of celestial coordinates.

1.1.4 Solar Arrays

The Space Telescope solar arrays will provide power to the spacecraft. The arrays are mounted on opposite sides of the HST, on the forward shell of the SSM. Each array stands on a four-foot mast that supports a retractable wing of solar panels 40 ft long and 8.2 ft wide.

The arrays rotate so the solar cells face the sun as much as possible. Each wing's solar cells absorb the sun's energy, and the array electronics convert that light energy into electrical energy. This energy goes to the spacecraft's electrical power subsystem for use or storage. Power is delivered by the batteries, which are charged by the solar arrays.

When the HST moves into the earth's shadow during each orbit, the arrays cannot collect energy.

1.1.5 Computers

There are two computers in the Hubble Space Telescope. The data management subsystem, through the DF-224 computer, handles data and command transmission between the HST systems and with ground control. The Scientific Instrument Control and Data Handling (SI C&DH) unit controls the SIs, receives and formats science data, and sends it to the communications system for transmission to earth.

1.2 THE HUBBLE SPACE TELESCOPE PROGRAM

The Hubble Space Telescope project is a multi-phase NASA program aimed at orbiting a large observatory in space for use by the international astronomical community. The program has five distinct phases:

- Development, assembly, and testing of the HST.
- Launch and deployment of the completed Space Telescope.
- Verification of the system and scientific functions of the HST.
- Operations employing the HST and its scientific instruments to produce information about the universe.
- Maintenance of the spacecraft as needed to ensure and extend its scientific mission.

Coordinating the overall program as the project management center is the staff at George C. Marshall Space Flight Center, in Huntsville, AL. Marshall is working with Kennedy Space Center, where the HST will be launched; Johnson Space Center, which will operate as Mission Control during deployment; Goddard Space Flight Center, which will be the ground control center during the verification and operation phase; the European Space Agency, which is contributing several vital components; the Space Telescope Science Institute, which will conduct science operations; an international team of astronomers organized as principal instrument developers and observers; prime contractors Lockheed Missiles & Space Company and Perkin-Elmer Corp.[1]; and many subcontractors who contributed to this program.

1.2.1 Development Phase

The Hubble Space Telescope project represents over 50 years of inquiry and study into the possibility of an orbiting observatory for astronomers. Led by NASA's Marshall Space Flight Center, astronomers and contractors have worked on the development of a large space telescope and its scientific instruments since Congress authorized the program in 1977. Marshall administered the design and development of the Space Telescope and instruments under the auspices of the NASA Office of Space Sciences and Applications.

Lockheed Missiles & Space Company, Sunnyvale, CA, and Perkin-Elmer Corporation, Danbury, CT, are the joint prime contractors for the Hubble Space Telescope project and are responsible to Marshall for project development. Lockheed built or supervised subcontract development of much of the equipment and the entire SSM, then assembled and test-verified the completed Space Telescope.

Perkin-Elmer (P-E) designed and built the OTA, including the telescope's primary and secondary mirrors, and the fine guidance sensors and other optical subsystems.

A group of international astronomers, called principal investigators, led development teams that created the five scientific instruments. Goddard Space Flight Center, in Greenbelt, MD, is responsible for the development and in-flight testing of the instruments. The instruments, principal investigators and their organizations, and the team subcontractors appear in Table 1-2.

The complete list of contractors who built Space Telescope instruments and equipment is shown in Table 5-2.

After building the separate components, the various developers and subcontractors sent the equipment to Lockheed. Sealed in a sterile

Table 1–2 Instrument Development Teams

Instrument	Principal Investigator	Team Subcontractor
Faint Object Camera	F. D. Macchetto European Space Agency	Dornier Corporation British Aerospace Matra-Espace
Faint Object Spectrograph	R. J. Harms, Applied Research Corp.	Martin Marietta Corporation
Goddard High Resolution Spectrograph	J. C. Brandt, Goddard Space Flight Center	Ball Aerospace
High Speed Photometer	R. C. Bless, University of Wisconsin	Space Astronomy Lab, University of Wisconsin
Wide Field/ Planetary Camera	J. A. Westphal, California Institute of Technology	Jet Propulsion Lab

[1]Now Hughes Danbury Optical Systems, Inc., ref. Chapter 5.

clean room, the entire Space Telescope was assembled, then tested under launch, liftoff, and space conditions.

Figure 1-3 shows the assembled Space Telescope in Lockheed's clean room prior to final pre-shipment testing.

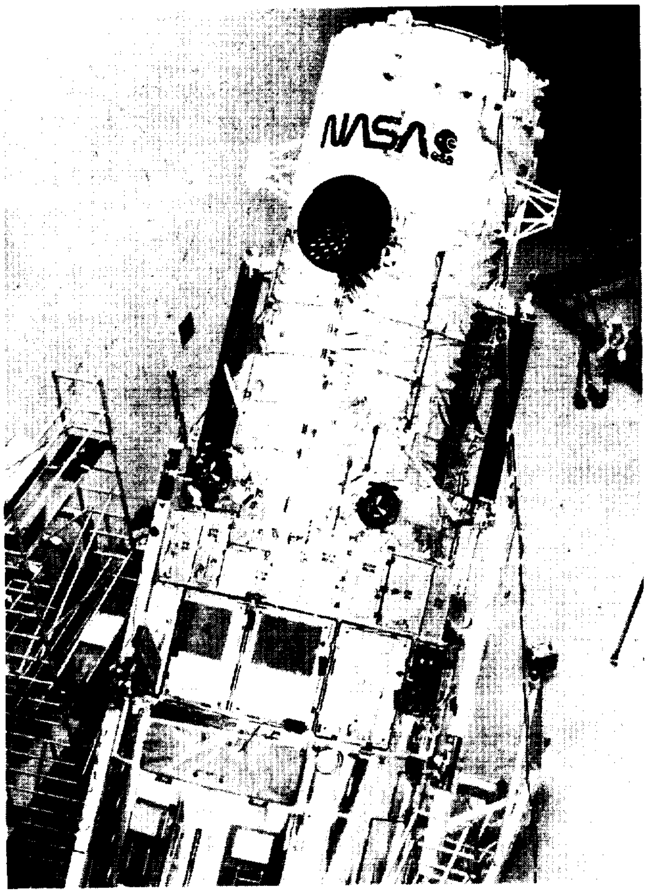


Figure 1-3 Space Telescope Assembled

The tests completed, Lockheed and NASA flew the Space Telescope to Kennedy Space Center. At Kennedy, the Space Telescope underwent more tests to ready the spacecraft for its launch date.

Once developed and tested, the Hubble Space Telescope moves into the program's four major operational phases: launch and deployment, orbital and scientific verification, science operations, and in-orbit maintenance.

1.2.2 Launch-and-Deployment Phase

During the launch-and-deployment phase, both Kennedy and Johnson Space Centers share the responsibility for the Space Telescope program. Kennedy will place the Space Telescope in the cargo bay of the Space Shuttle and run all pre-launch activities. When the Space Shuttle lifts off, Johnson Space Center's Mission Control, in Houston, TX, will take over control of the flight. Johnson has trained the Shuttle astronauts to perform extravehicular activities designed specifically for the Space Telescope, such as manually turning on the spacecraft's internal power. During the Shuttle operation, JSC Mission Control will work with the Orbiter crew and the Space Telescope Operations Control Center (STOCC) at Goddard Space Flight Center.

Once in orbit, the Space Shuttle crew will deploy the Space Telescope. The crew will use the Shuttle remote manipulator system (RMS) arm to position the HST in space. After a checkout by the STOCC and Mission Control, the telescope will be released. The Shuttle will remain nearby in case it is needed. See Figure 1-4 for a depiction of the sequence.

1.2.3 Verification Phase

The Hubble Space Telescope will undergo functional systems testing over its first 30 days in space. This phase is called Orbital Verification and is controlled by Marshall Space Flight Center. Running internal tests on the HST subsystems will ensure the spacecraft's systemic ability to function in space.

Scientific verification, run by Goddard Space Flight Center, will put all science instruments through tests to ascertain that the instruments work and conform to NASA's specifications. After verification of all scientific instruments, the Hubble Space Telescope will enter its formal operational phase.

Figure 1–4 Space Telescope Deployment Sequence (From Left to Right)

1.2.4 Operational Phase

During the post-verification operational phase, the Hubble Space Telescope observatory system will use the following complex network:

- The HST spacecraft
- The NASA communications network of Tracking and Data Relay Satellites (TDRS) and domestic satellites
- The Space Telescope ground system, comprised of the following:
  - The STOCC, which controls mission operations through the Payload Operations Control Center (POCC) at Goddard
  - The Space Telescope Science Institute (STScI), in Baltimore, MD, where scientific programs for the Space Telescope will be planned

The STOCC is the primary center of ground operations. It provides minute-to-minute control of the spacecraft when required, and the STOCC schedules, plans, and supports all science observations.

The STOCC has two subordinate organizations. The POCC is the ground-based nerve center for the HST. It sends all communication to the spacecraft and monitors telemetry data. The Science Support Center (SSC) is the link between the POCC and the Space Telescope

Science Institute. The SSC supports scientific operations, from quick checks of incoming data for accuracy to processing and managing the completed data package.

The STScI is the scientific operations center. It is responsible for all operational science and for selecting observers. Teams of astronomers assist the Institute staff in planning, selecting, observing, and analyzing the astronomical data collected by the Hubble Space Telescope.

The astronomy teams working at the STScI will have an agenda of specific celestial targets and objectives. When the STScI selects a target, it will send targeting coordinates to the Space Telescope via the TDRS communication satellites. The HST will use the coordinates of two guide stars, designated by STScI's star catalog as reference points. The HST DF-224 computer will maneuver the spacecraft, using data provided by the pointing subsystem. The HST fine guidance sensors will lock onto the guide stars, and, from that position, point the telescope at the target itself. This system is so precise and stable that it could hold a beam of light squarely on a dime 600 miles away and not waver more than the diameter of the coin. See Figure 1-5.

Any of the five scientific instruments or a fine guidance sensor then will collect data on the specified target. That information will be sent by the instrument or sensor to the SI C&DH computer, then sent to the STOCC during a scheduled transmission. From there the data will go to the Science Institute for distribution to the science teams (see Figure 1-6).

1.2.5 Maintenance Phase

Ninety percent of the equipment and instrumentation on the HST has a backup or identical unit. For example, most of the scientific instruments back up each other because they overlap slightly in function. There may be times, nonetheless, when equipment will need repair. As

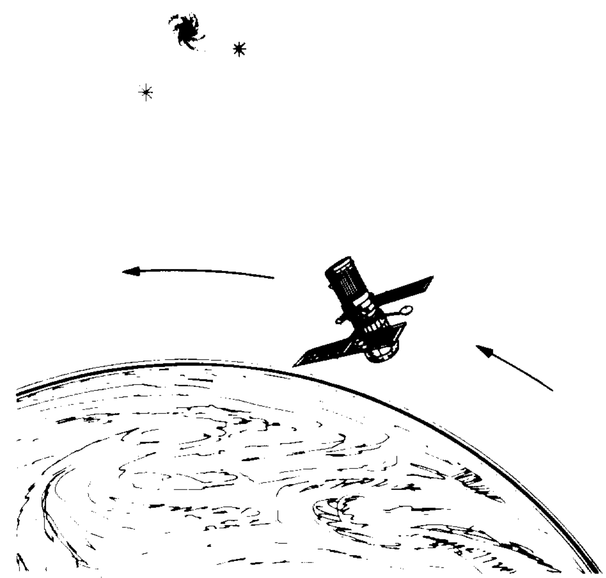


Figure 1-5 HST Locks on Target

one example, the HST batteries will be replaced after several years. Maintenance missions will be scheduled to replace equipment or instruments and to extend the lifetime of the Space Telescope. For example, NASA already is considering a second generation of scientific instruments that could replace the original group. Instruments will be exchanged in orbit, not on the ground.

Responsibility for this phase currently lies with Marshall, but Goddard will oversee maintenance eventually.

During a maintenance mission, the Space Shuttle will bring up equipment, match the Space Telescope's orbit, and grab the HST with the Shuttle RMS arm. After ground commands stow HST antennas and solar arrays, the arm will place the HST onto a special, horseshoe-shaped platform in the Shuttle cargo bay. The Space Telescope and the replacement part, latched down in a carrier, are depicted in Figure 1-7.

All support equipment and scientific instruments are located on the HST for easy access by a space-suited astronaut. The bays have hand

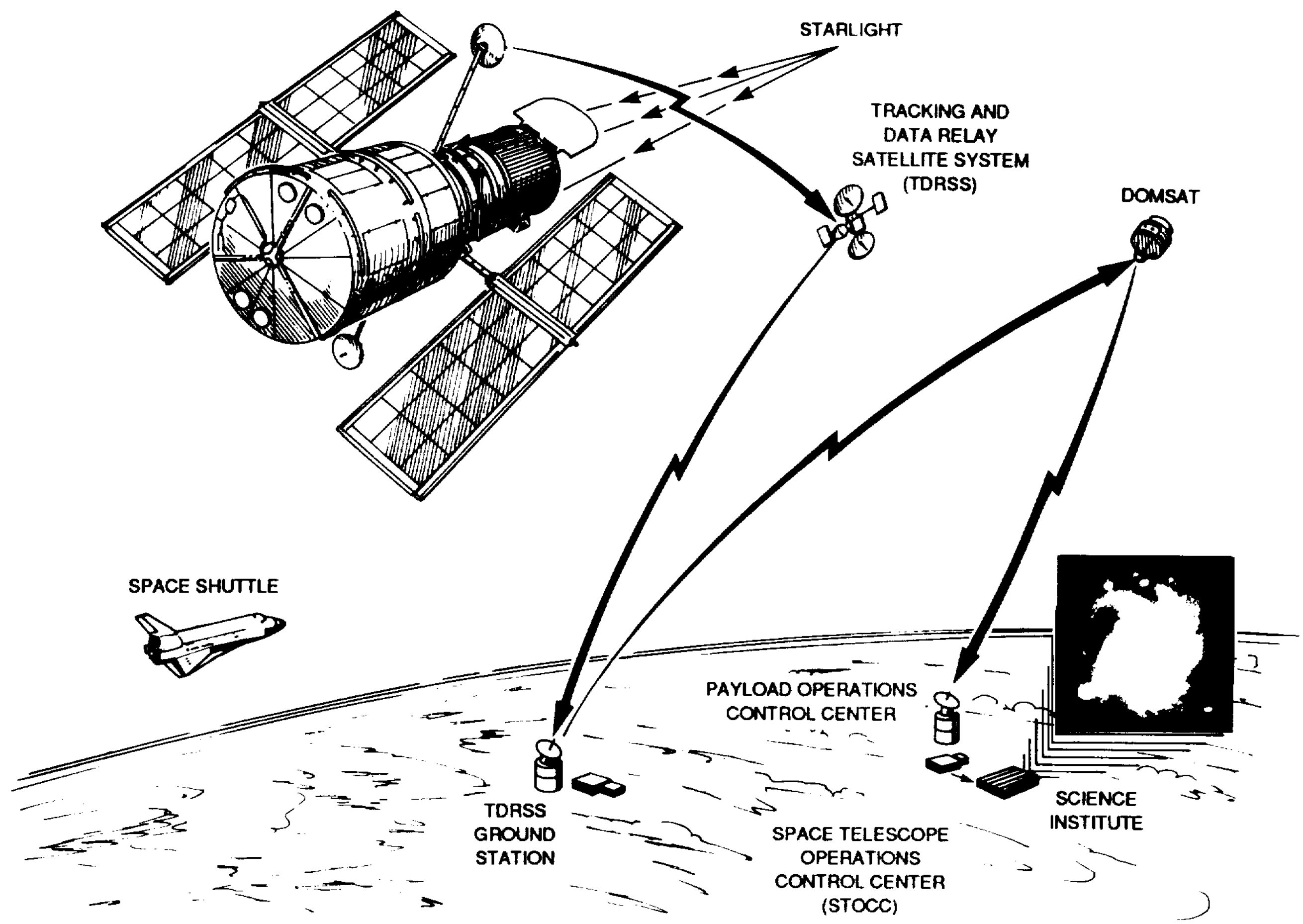


Figure 1–6 HST Network Collecting Data

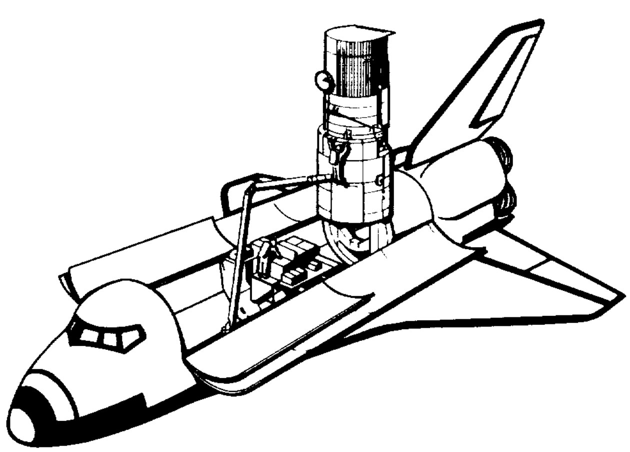


Figure 1–7 HST Berthed in Shuttle Bay

and footholds for the crew, and doors opening onto most equipment and instrument compartments. The crew will make repairs while the HST stands in the cargo bay. Then the Shuttle will release the Space Telescope to orbit again.

The Shuttle also can move the HST to a higher orbit, called reboosting. This may be required due to the atmospheric drag on the HST, which is slight but enough to cause the spacecraft orbit to decay and eventually bring the spacecraft back to earth.

Eventually, maintenance missions may be performed on Space Station Freedom using an Orbital Maneuvering Vehicle that brings the HST to the station.

Section 2
THE HUBBLE SPACE TELESCOPE SYSTEMS

The Hubble Space Telescope orbits the earth and observes specific celestial targets selected by the Space Telescope Science Institute. The spacecraft has three interacting systems:

- The Support System Module (SSM), an outer structure that houses the other systems and provides services such as power, communication, and control.
- The Optical Telescope Assembly (OTA), which collects and concentrates the incoming light in the focal plane for use by the scientific instruments.
- Five scientific instruments, four housed in an aft section focal plane structure and one placed along the circumference of the spacecraft, all controlled by the Scientific Instrument Control and Data Handling unit (SI C&DH).

Peripheral equipment supports the operation and maintenance of the Space Telescope. Three fine guidance sensors precisely point the spacecraft; two solar arrays re-energize the HST's batteries; and four antennas send and receive communications between the Space Telescope and ground control.

Figure 2-1 shows the configuration of the Hubble Space Telescope.

The Space Telescope performs very much like a ground observatory with a medium-sized reflecting telescope. The SSM, like an observatory, powers, points, and communicates with

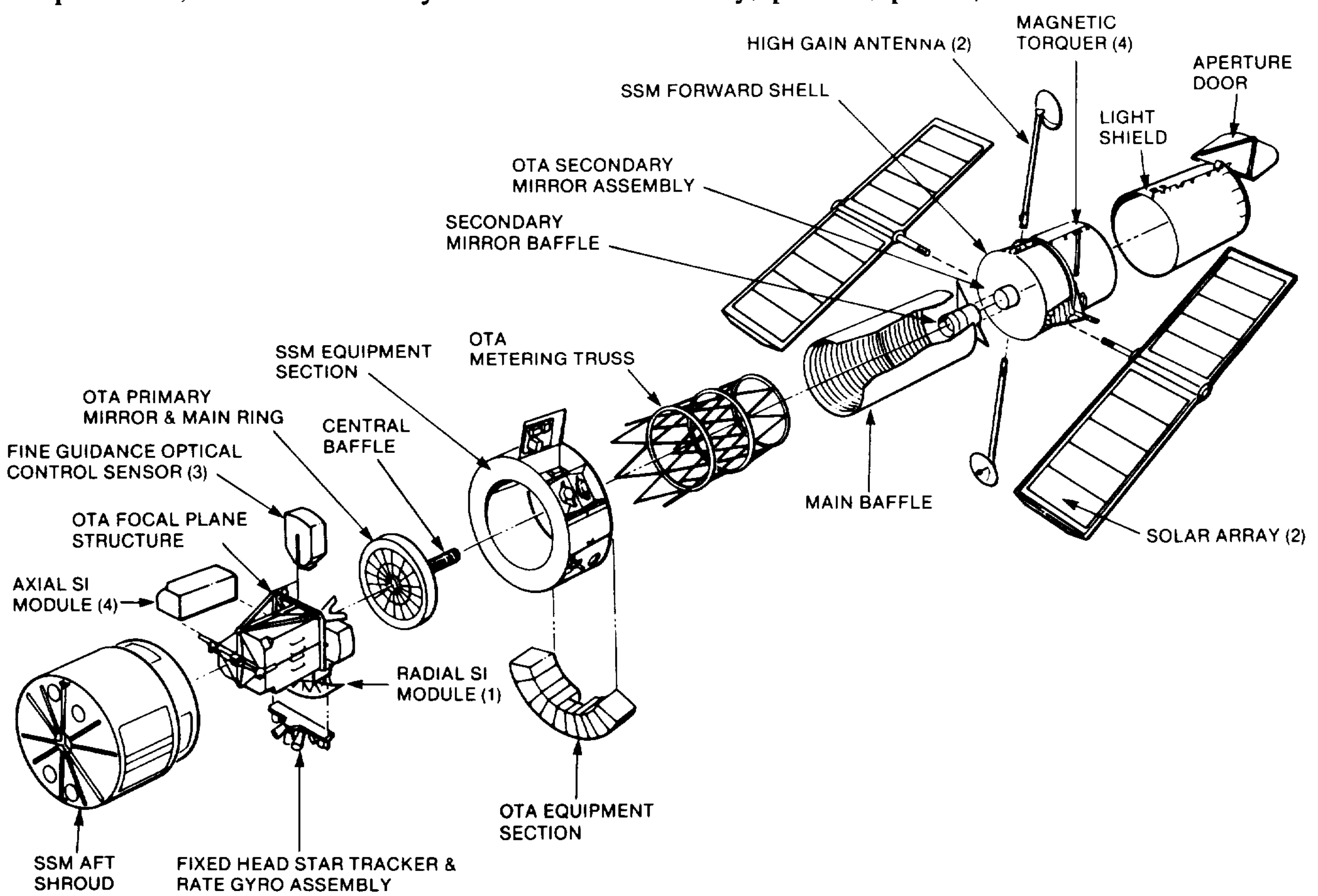


Figure 2–1 Hubble Space Telescope Configuration

the telescope assembly to ready an observation. Light from the observed target passes through the telescope and into one or more of the scientific instruments, where the light is recorded. This information goes to on-board computers for processing, then either is stored or sent to earth, via the spacecraft communication system, for analysis.

The Space Telescope will make its observations while orbiting the earth. It will complete one orbit every 97 minutes. The spacecraft will maintain its orbital position along three axial planes. The primary axis, V1, runs through the center of the telescope, end to end. The other two axes parallel the solar array masts (V2) and the high gain antenna masts (V3) (see Figure 2-2). The HST will point and maneuver to new targets by rotating around two of the three spacecraft axes.

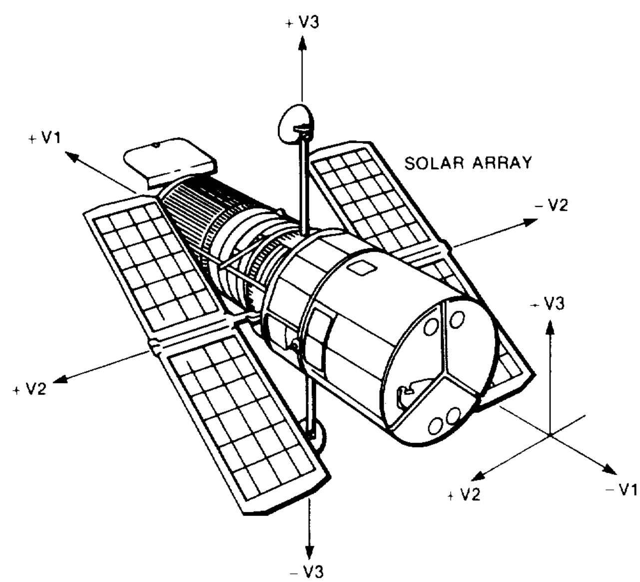


Figure 2–2 Hubble Space Telescope Axes

References to these axes are used by the HST pointing instruments to aim at a target in space, position the solar arrays, or change orientation in orbit.

2.1 THE SUPPORT SYSTEMS MODULE

The Support Systems Module provides the external structure that houses the Optical Telescope Assembly and the scientific instruments. It also contains the electrical power, data management, thermal control, and communications systems for the entire Space Telescope. Design features include:

- An outer structure of interlocking shells
- Rotating reaction wheels and magnetic torquers to orient and stabilize the HST
- Two solar arrays to provide power
- Communications antennas
- A ring of equipment-section bays that contain electronic components, such as batteries, and communications equipment
- Computers to operate the spacecraft systems and handle data
- Reflective surfaces for thermal protection
- Outer doors, latches, and rails designed for astronauts to use during in-orbit maintenance

Some of these features are illustrated in Figure 2-3.

The major component subsystems of the SSM are the:

- Structural and mechanisms subsystem
- Instrumentation and communications subsystem
- Data management subsystem
- Pointing control subsystem
- Electrical power subsystem
- Thermal control subsystem
- Safing (contingency) subsystem

A team of contractors and subcontractors designed and built the components for the structure. The full list of team members is in Chapter 5.

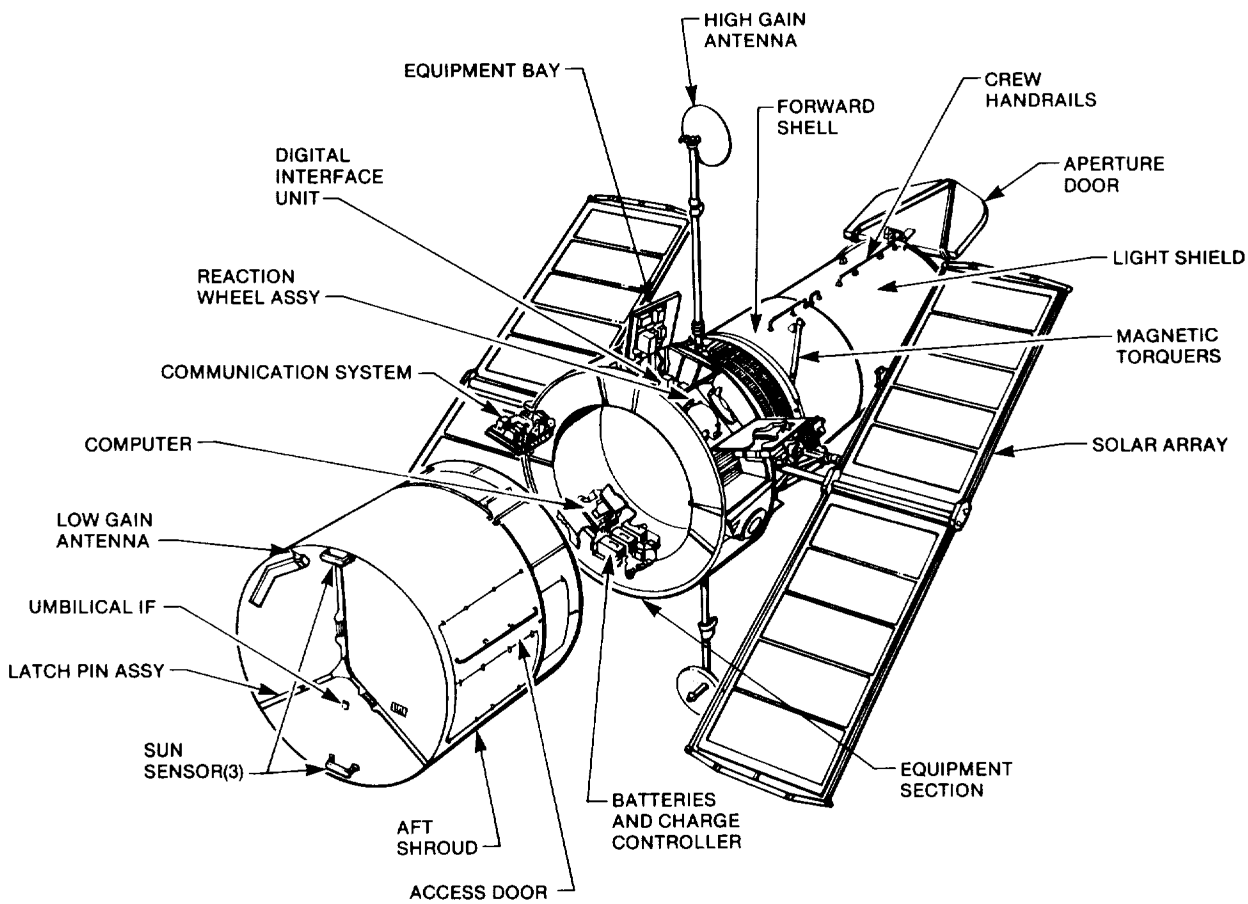


Figure 2-3 Design Features of the Support Systems Module

2.1.1 Structural and Mechanisms Subsystems

The outer structure of the SSM is composed of stacked cylinders, with the aperture door on top and the aft bulkhead on bottom. Fitting together are the light shield, the forward shell, the SSM equipment section, and the aft shroud/bulkhead. They are made by Lockheed Missiles & Space Company and are identified in Figure 2-4. Figure 2-5 shows the Hubble Space Telescope assembled.

2.1.1.1 Aperture Door. The aperture door, approximately 10 ft (3 m) in diameter, covers the opening to the telescope's light shield. The door is made from honeycombed aluminum sheets. The outside is covered with solar-reflecting material, and the inside is painted black to absorb stray light.

The door opens to a maximum of 105 degrees from the closed position. The telescope aperture allows for a 50-degree field of view centered on the V1 axis. Sun-avoidance sensors on the door provide ample warning to close the door before sunlight can damage the telescope's optics. The door begins closing when the sun is within 35 degrees of the V1 axis and finishes closing by the time the sun reaches 20 degrees of V1. This takes no more than 60 seconds.

The Space Telescope Operations Control Center (STOCC) can override the protective door-closing mechanism for observations that fall within the 20-degree limit. An example is

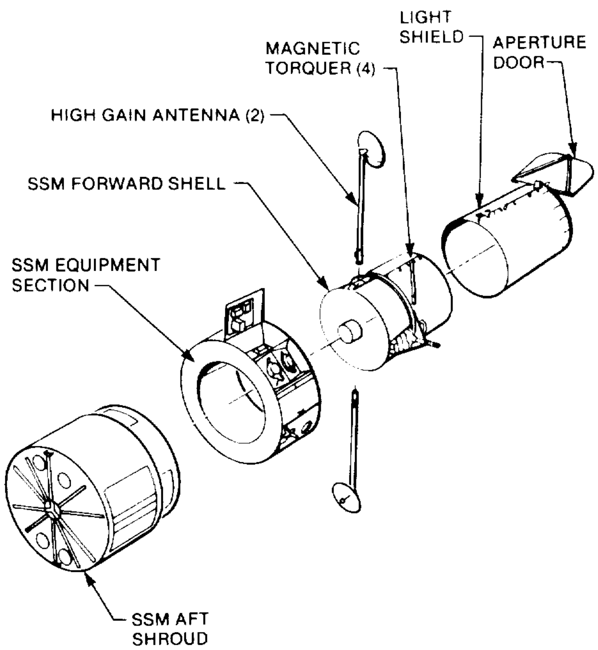


Figure 2–4 The Structural Components of the SSM

observing a bright object, using the dark limb, or edge, of the moon to partially block the light.

2.1.1.2 Light Shield. The HST light shield blocks out stray light. It connects to the aperture door and to the forward shell. On the outer skin on opposite sides are latches to secure the solar arrays and the high-gain antenna when they are stowed. Near the array latches are scuff plates, large metal plates on struts that extend around 30 in. from the surface of the spacecraft. The scuff plates and trunnions will secure the Space Telescope within the Shuttle cargo bay. The light shield supports the forward low-gain antenna and its communications waveguide, and the three magnetometers. Hand rails encircle the shield, and there are foot restraint supports for astronauts operating on the HST.

The shield is 13 ft (4 m) long, with an internal diameter of 10 ft (3 m). It is machined from magnesium, with a stiffened, corrugated-skin barrel covered by a thermal blanket. Internally the shield has ten light baffles, painted flat black to suppress stray light. Figure 2-6 shows the aperture door and light shield.

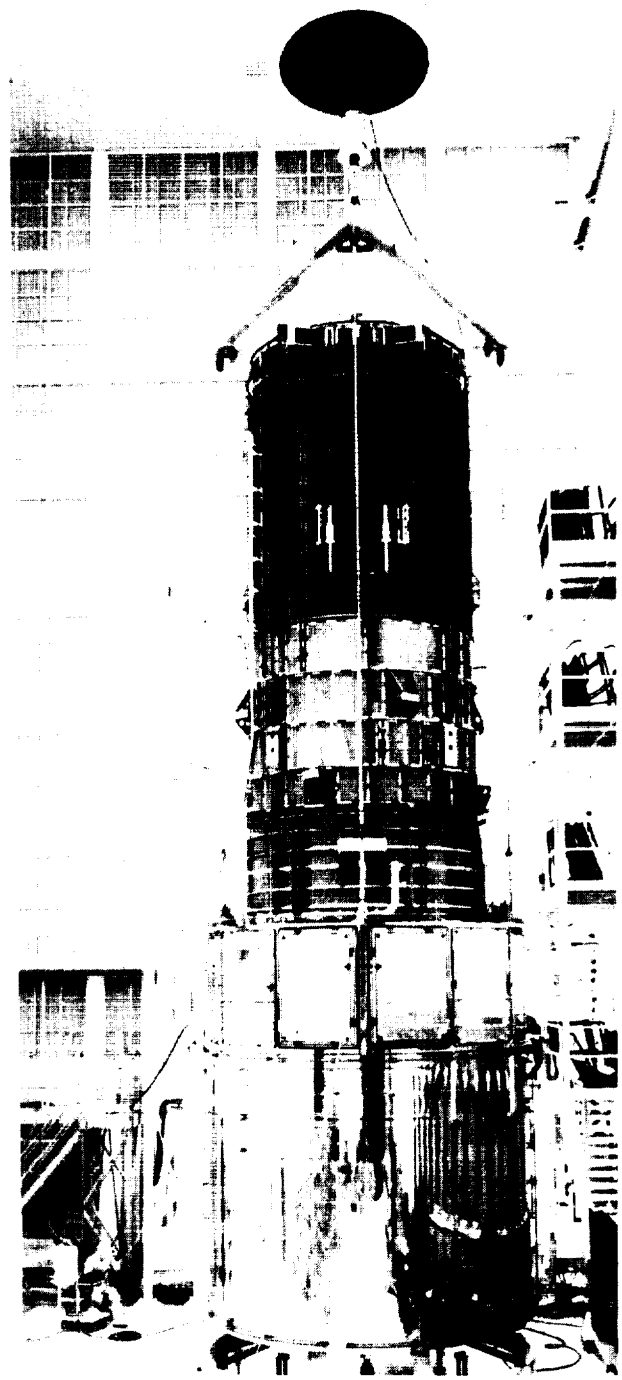


Figure 2–5 HST Assembly

2.1.1.3 Forward Shell. The forward shell is the central section of the structure and houses the telescope assembly main baffle and secondary mirror. The solar arrays and high-gain

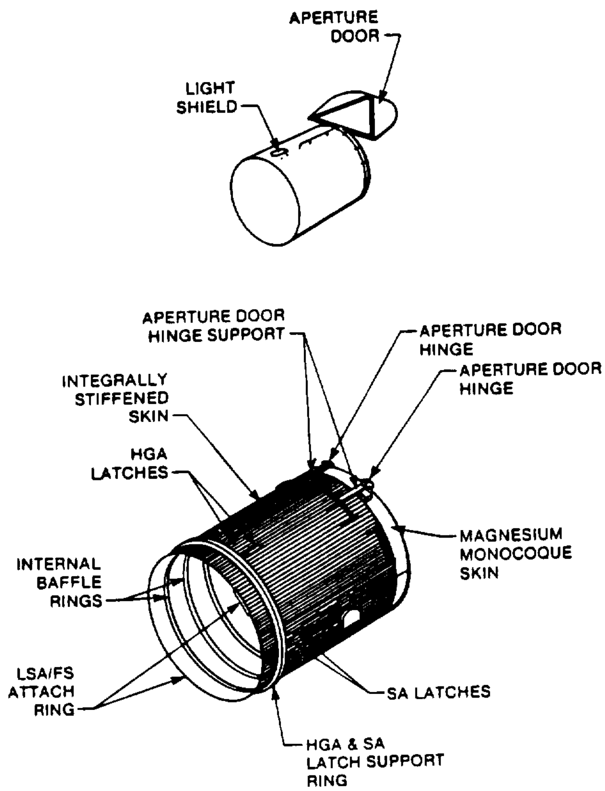


Figure 2–6 Aperture Door and Light Shield

antennas, when stowed, are latched flat against the forward shell and the light shield. Four magnetic torquers are placed 90 degrees apart around the circumference of the forward shell. The outer skin has two grapple fixtures, next to the high-gain antenna drives, where the Orbiter remote manipulator system can attach to the SSM. The forward shell also has a trunnion, used to lock the HST into the Shuttle cargo bay, and hand and foot holds (see Figure 2-7).

The forward shell is 13 ft (4 m) long and 10 ft (3 m) in diameter. It is machined from aluminum plating, with external reinforcing rings and internal stiffened panels. The rings are on the outside to assure clearance for the OTA assembled inside. Thermal blankets cover the exterior.

2.1.1.4 Equipment Section. A ring of storage bays encircling the SSM contains 90% of the electronic components to run the spacecraft. This includes equipment serviced during extravehicular activities by Orbiter crews performing in-orbit maintenance and repair.

The equipment section (SSM-ES) is a doughnut-shaped barrel that fits between the forward shell and aft shroud. The section contains 10 bays for equipment and two bays to support aft trunnion pins and scuff plates. Going clockwise from the +V3 (top) position, the bays contain:

Bay 8 — Pointing control subsystem
Bay 9 — Reaction wheel assembly
Bay 10 — Scientific Instrument Control and Data Handling Unit
Unnumbered trunnion support bay
Bay 1 — Data management unit
Bay 2 through Bay 4 — Power equipment
Unnumbered trunnion support bay
Bay 5 — Communications
Bay 6 — Reaction wheel assembly
Bay 7 — Mechanism control unit

Figure 2-8 shows the location of the bays and the contents of each bay.

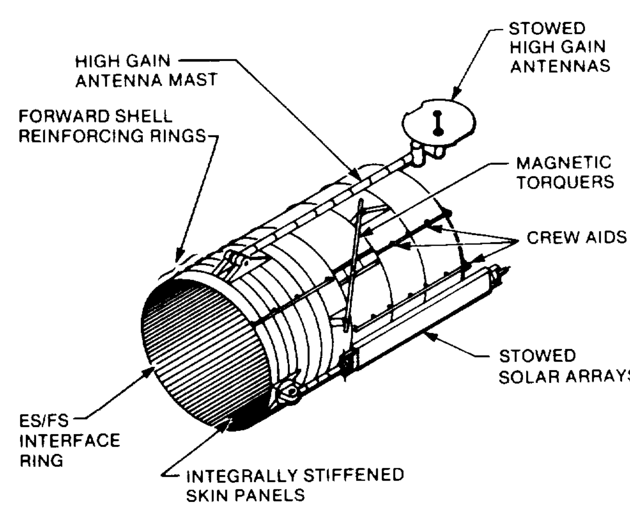


Figure 2–7 SSM Forward Shell

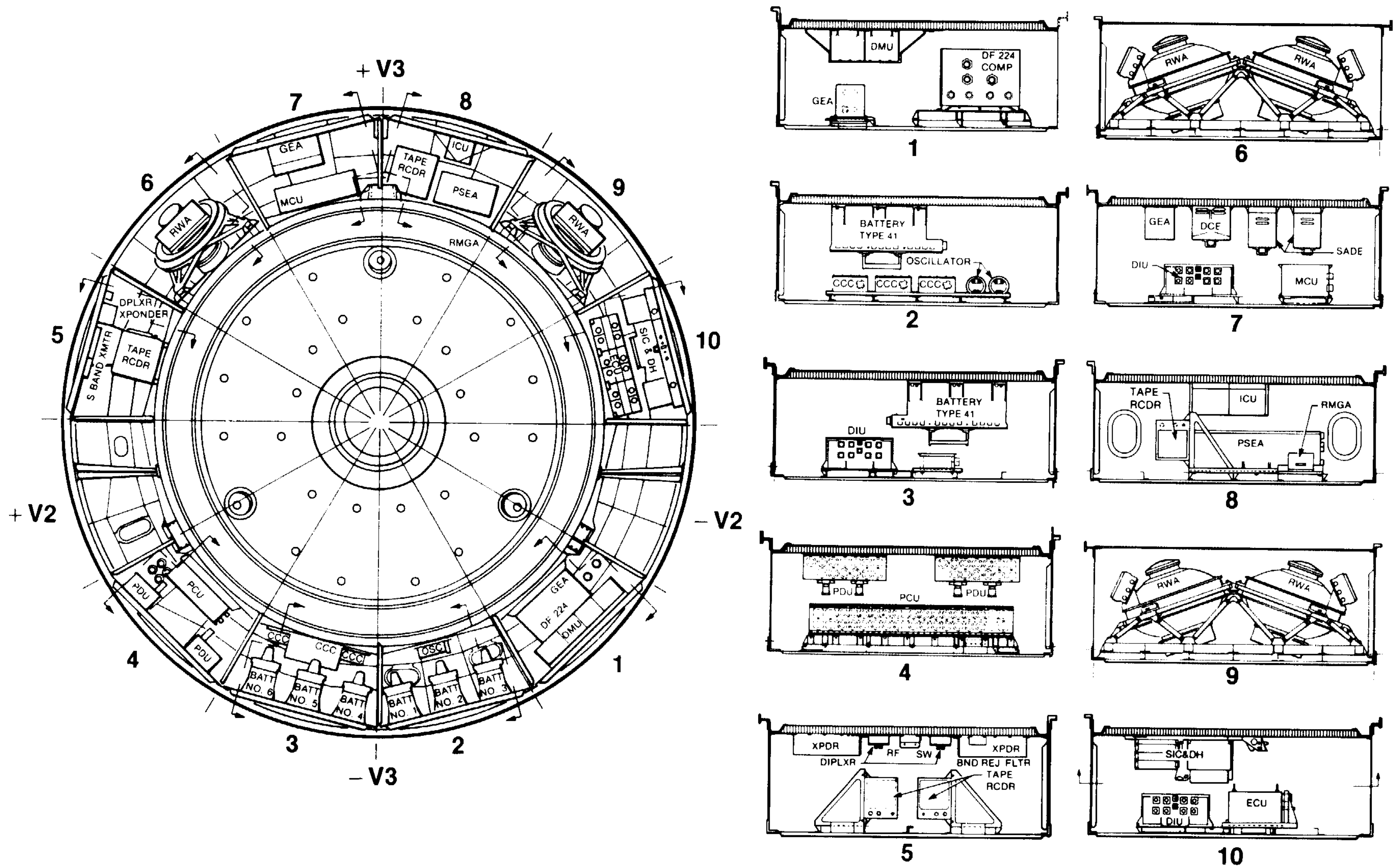


Figure 2-8 SSM Equipment Section Bays and Contents

Each bay is shaped like a trapezoid, with the outer diameter (the door) greater than the inner diameter, 3.6 ft (1 m) to 2.6 ft (0.78 m). The bays are 4 ft (1.2 m) wide and 5 ft (1.5 m) long. The section has machined and stiffened aluminum frame panels attached to an inner aluminum barrel. Eight bays have flat honeycombed aluminum doors mounted with equipment. Bays 6 and 9 have thermal stiffened panel doors providing covering for the reaction wheels. A forward frame panel and aft bulkhead enclose the section. Six mounts on the inside of the bulkhead hold the OTA in place.

2.1.1.5 Aft Shroud and Bulkhead. The aft shroud houses the focal plane structure containing the four axial scientific instruments. The three fine guidance sensors and the Wide Field/Planetary Camera are housed radially near the connecting point between the aft shroud and equipment section. On the outside of the shroud are doors so Shuttle astronauts can remove and change equipment and instruments easily. Hand rails and foot restraints for the crew are located along the length and circumference of the shroud. Interior lights can illuminate the compartments containing the scientific instruments during maintenance or removal of an instrument. The shroud is made of aluminum, with a stiffened skin, internal panels and reinforcing rings, and 16 external and internal longeron bars for support. It is 11.5 ft (3.5 m) long and 14 ft (4.3 m) in diameter.

The aft bulkhead contains the umbilical connections between the HST and the Orbiter, used during launch/deployment and in-orbit maintenance. The rear low-gain antenna attaches to the bulkhead. It is made of two-inch thick honeycombed aluminum panels and three radial aluminum support beams.

The shroud and bulkhead structurally support a gas purge system used to prevent contamination of the scientific instruments prior to launch. All vents used to expel the gases are light-tight; i.e., no stray light can enter to interfere with those wavelengths concentrated in the OTA focal plane (see Figure 2-9).

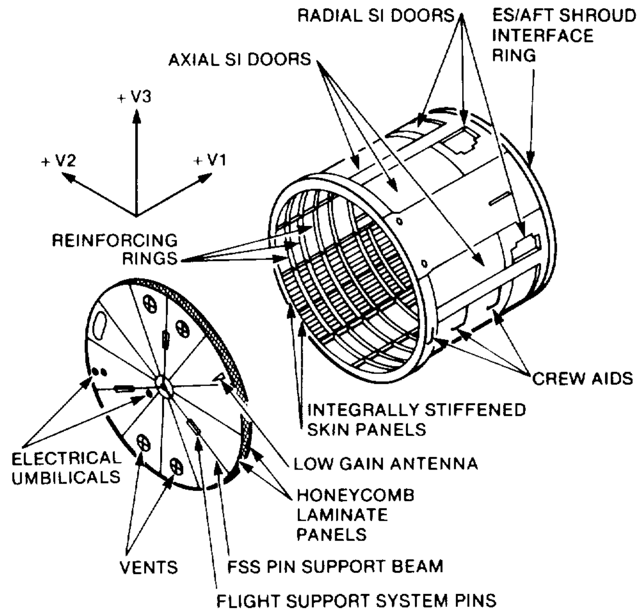


Figure 2-9 SSM Aft Shroud and Bulkhead

2.1.1.6 Mechanisms. Along the SSM structure are mechanisms used to perform various functions. The mechanisms include:

- Latches to hold antennas and solar arrays
- Hinge drives to open the aperture door and erect the arrays and antennas
- Gimbals to move the high-gain antenna dishes
- Motors to power the hinges and latches and to rotate the arrays and antennas

There are nine latches: four for the antennas, four for the arrays, and one for the aperture door. They latch and release using a four-bar linkage and are driven by a stepper motor called a rotary-drive actuator.

There are three hinge drives: one for each high-gain antenna, and one for the door. The hinges also operate using a rotary-drive actuator.

Both hinges and latches have hex wrench fittings so an astronaut can manually operate the mechanism to deploy the door, antenna, or array if a motor fails.

2.1.2 Instrumentation and Communications Subsystem

The instrumentation and communications subsystem provides the communications loop between the HST and the TDRS satellites, sending and receiving messages, commands, and data through the high and low gain antennas and passing the information to the data management subsystem. High gain and low gain refer to the effectiveness of the antenna, higher being more effective. The high gain antennas have larger signal-collecting areas.

The communications subsystem provides multiple-channel and single-channel access (broadcast) systems for transmitting data and messages. The multiple-access system can send commands and engineering data on either or both channels simultaneously. Single-access transmits science data as it is gathered, or taped science and engineering data under contingency conditions.

2.1.2.1 High-Gain Antennas (HGA). The two high-gain antennas are the primary communications links to relay science data to the ground during normal operation, using the single-channel access system. When in sight of TDRS satellites, the antennas can transmit about 90 minutes maximum during each 97-minute orbit. When the high-gain antennas are not extended, the low-gain antennas are used.

Each high-gain antenna is a parabolic reflector (dish) antenna mounted on a mast, with a two-axis gimbal mechanism and electronics to rotate the antenna 100 degrees in either direction. General Electric designed and made the antennas from honeycomb aluminum and graphite-epoxy face sheets. Figure 2-10 shows the antenna dish.

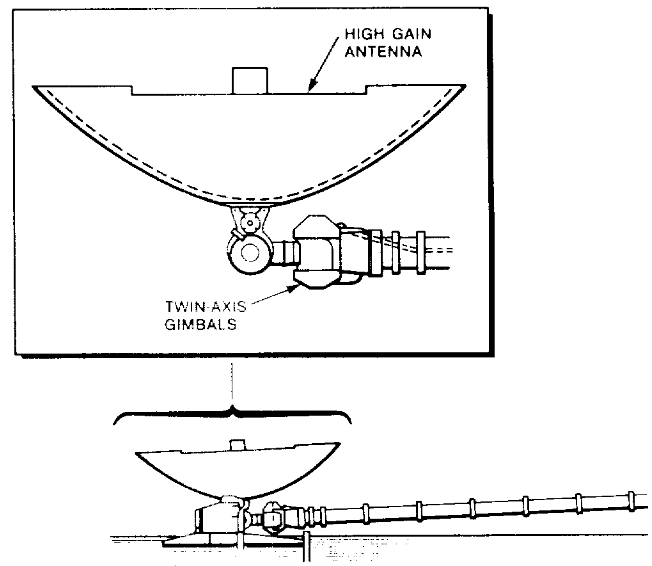


Figure 2-10 The High-Gain Antenna

Each antenna can point to a fixed position with a one-degree pointing error. Accuracy is not as crucial for communications as for pointing the telescope, where the OTA must point accurately to within 0.01 arcsec of a given position. Antenna movement will not affect the HST stability and, thus, line of sight. The antennas transmit over two frequencies: 2255.5 MHz or 2287.5 MHz (plus or minus 10 MHz).

2.1.2.2 Low-Gain Antennas (LGA). The low-gain antennas receive ground commands and transmit engineering data using the multiple-channel access system. They are on the light shield and aft bulkhead of the spacecraft, set 180 degrees apart. Each antenna is a spiral cone, with frequency ranges from 2100 to 2300 MHz. The low-gain antennas, manufactured by Lockheed, can be used while the HST is placed in orbit or retrieved, or in emergencies when the high-gain antennas cannot be used.

2.1.3 Data Management Subsystem

The data management subsystem (DMS) receives communications, calibrations, and commands from the Space Telescope Operations Control Center, and data from the SSM systems and the scientific instruments. Then it processes, stores, and sends the information as requested. The subsystem components are:

- DF-224 computer
- Data management unit
- Four data interface units
- Three engineering/science tape recorders
- Two oscillators

They are located in the equipment section, except for one data interface unit stored in the OTA.

This subsystem receives and sends four types of signals:

1. Commands sent to the HST systems
2. Received data, such as commands or system status data
3. Scientific data from the SI C&DH
4. System outputs, such as clock signals

Figure 2-11 is the subsystem functional diagram.

2.1.3.1 DF-224 Computer. The DF-224 computer, built by Rockwell Autonetics, is a general-purpose digital computer used for onboard engineering computations. The computer must execute stored commands, format data calculations into radio signals (telemetry), orient the solar arrays toward the sun, monitor the power system, and point the antennas. It has stored programs specifically written to handle these functions.

The DF-224 configuration is three central processing units (CPU), two as backup; six memory units (MU), with up to 48,000 words total; three input/output units (IOU), two as backup; and

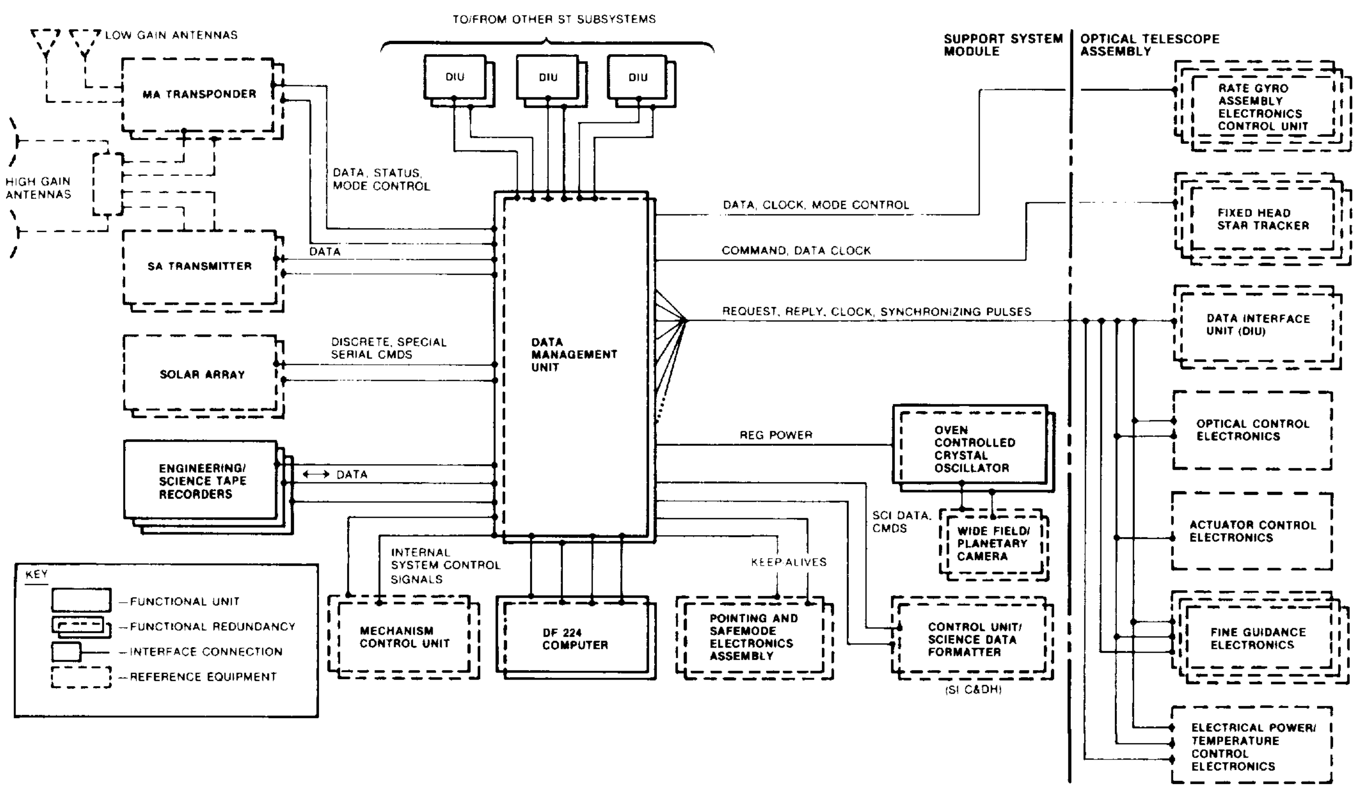


Figure 2-11 DMS Functional Block Diagram

six power converter units (PCU) assigned with overlapping functions as a safeguard. The DF-224 is 1.5 x 1.5 x 1 ft (0.4 x 0.4 x 0.3 m) and weighs 110 lb (50 kg). It is in bay 1 of the SSM equipment section (see Figure 2-12).

2.1.3.2 Data Management Unit. The data management unit (DMU), made by LMSC, links with the DF-224. It encodes and sends messages to selected HST units and all DMS units, powers the oscillators, and is the central HST timing source. The DMU also receives and decodes all incoming commands, then passes each processed command along to be executed.

The data management unit is an assembly of printed-circuit boards, interconnected through a backplate and external connectors. The unit weighs 83 lb (37.7 kg), measures 26 x 30 x 7 inches, (60 x 70 x 17 cm) and is attached to the door of equipment section bay 1 (see Figure 2-13).

The DMU receives science data from the SI C&DH. Engineering data, which consist of sensor status readings (temperature, voltages, etc.), come from each of the HST subsystems. These data can be stored in the on-board engineering/

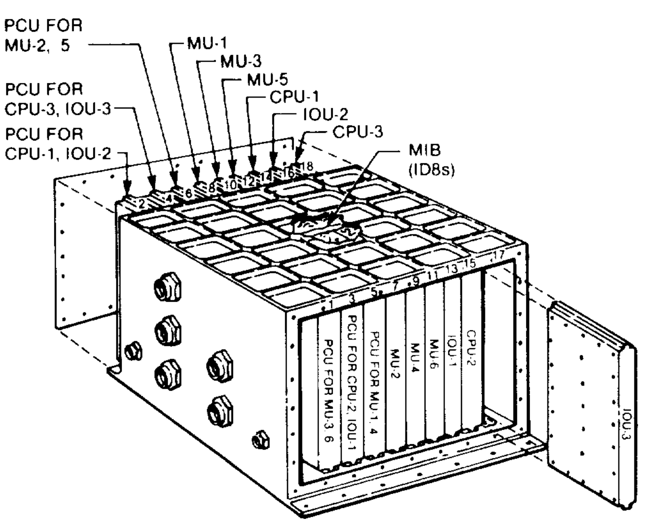


Figure 2-12 DF-224 Computer

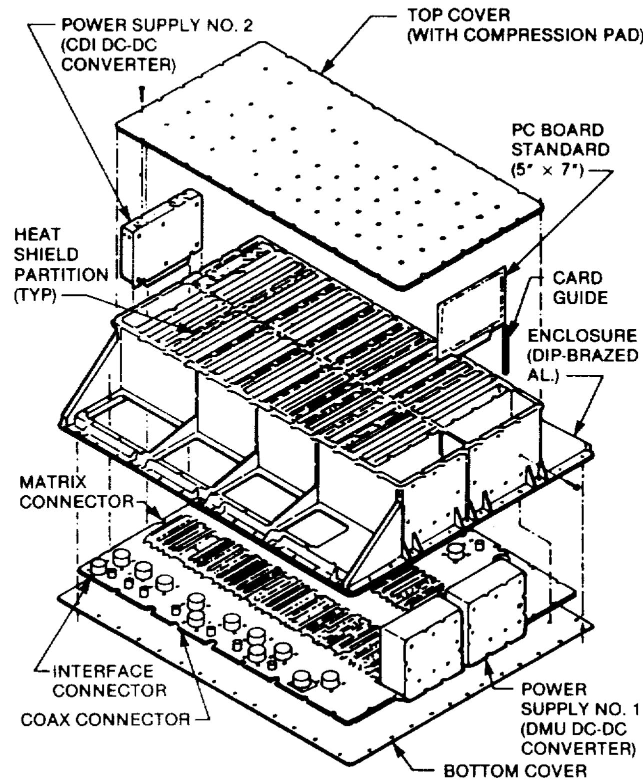


Figure 2-13 Data Management Unit Configuration

science tape recorders if direct telemetry via TDRS is unavailable.

The data management unit also selects the appropriate telemetry format required. For example, deployment format is used only when the LGAs are operational, and diagnostic format is for faster transmission when a subsystem performance needs immediate evaluation.

2.1.3.3 Data Interface Unit. The four data interface units (DIU), also engineered and built by LMSC, provide a command and data link between the data management subsystem and other HST subsystems. The data interface units receive instructions from the data management unit, perform the operations required, and pass data or status information back to the DMU. Each DIU connects to the DMU. The OTA data interface unit is in the OTA equipment section; the other units are in bays 3, 7 and 10 of the equipment section. As a safeguard, each DIU is two complete units in one; either part can handle the unit's functions. Each data interface unit is 15 x 16 x 7 in. (38 x 41 x 18 cm) and weighs 35 lb (16 kg).

2.1.3.4 Engineering/Science Tape Recorders. The data management subsystem includes three tape recorders to store engineering or science data that cannot be transmitted to the ground immediately. The recorders can hold up to one billion bits of information. Two recorders are used in normal operations; the third is a backup or for contingency operations. The recorders, each 12 x 9 x 7 in. (30 x 23 x 18 cm) in dimension and weighing 20 lb (9 kg), are stored in equipment section bays 1, 3, and 8.

2.1.3.5 Oscillator. The oscillator provides a highly-stable central timing pulse, required by the HST. It has a cylindrical housing 4 in. (10 cm) in diameter and 9 in. (23 cm) long and weighing 3 lb (1.4 kg). The oscillator and a backup are mounted in bay 2 of the SSM equipment section.

2.1.4 Pointing Control Subsystem

The pointing control subsystem (PCS) maintains Space Telescope positional stability and aligns the spacecraft to point to and remain locked on any specific target. The pointing subsystem is accurate to within 0.01 arcsec and can hold the telescope to that position with 0.007 arcsec stability. If the HST were in Los Angeles, it could hold a beam of light on a dime in San Francisco, without the beam straying from the coin's diameter.

The PCS maintains the telescope's position by locating two guide stars and maneuvering the HST to keep it in the same position relative to these stars. When specific target requests require realigning the spacecraft, the pointing system selects different reference guide stars and moves the Space Telescope until it is in the new position.

The pointing control subsystem includes five different types of sensors, the DMS computer, and two types of devices, called actuators, to move the spacecraft (see Figure 2-14). It also includes the pointing safemode electronics assembly and the retrieval mode gyro assembly, both used in the spacecraft contingency system. See section 2.1.7 for details on these assemblies.

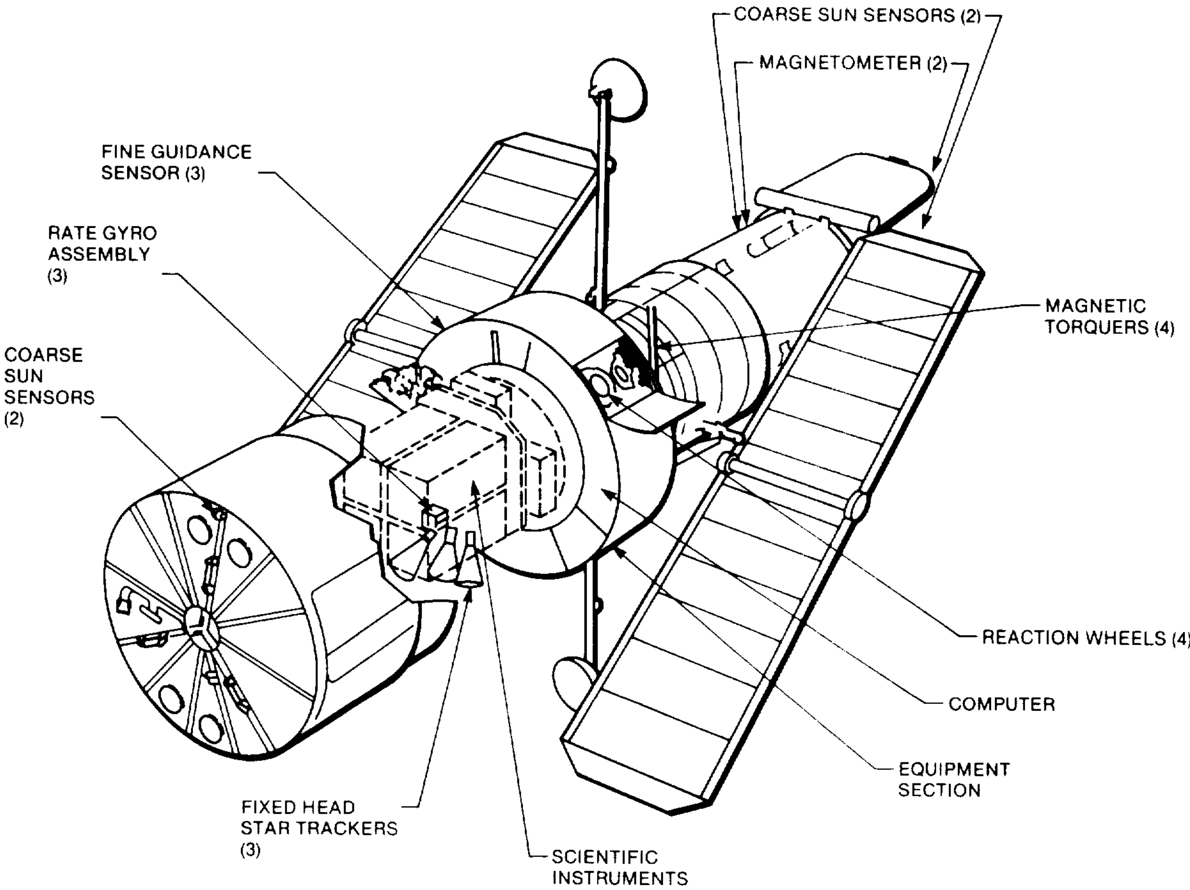
2.1.4.1 Sensors. The five types of sensors used by the PCS are the coarse sun sensors, the magnetic sensing system, the rate gyro assembly, the fixed-head star trackers, and the fine guidance sensors.

The four coarse sun sensors are sensing devices, located on the light shield and aft shroud, that send signals to the pointing safemode electronics assembly in bay 8 of the SSM equipment section. The coarse sun sensors measure the position of the sun. They also calculate the initial deployment position for the HST and determine when to begin closing the aperture door. Sun sensors position the HST during special sun-orientation modes in contingency operations.

The magnetic sensing system consists of two magnetometers, both on the front end of the light shield, that are connected to electronic units sending the data to the DF-224 computer. The system measures the HST's relative orientation with respect to the earth's magnetic field.

The rate gyro assembly consists of three rate-sensing units underneath the SSM equipment section and next to the fixed-head star trackers. These units send information to the electronic control unit inside bay 10. The assembly senses the spacecraft's rate of motion and position relative to the orbital plane so the pointing system can control the orientation of the line of sight of the Space Telescope.

A fixed-head star tracker is an electro-optical detector that locates and tracks a specific star



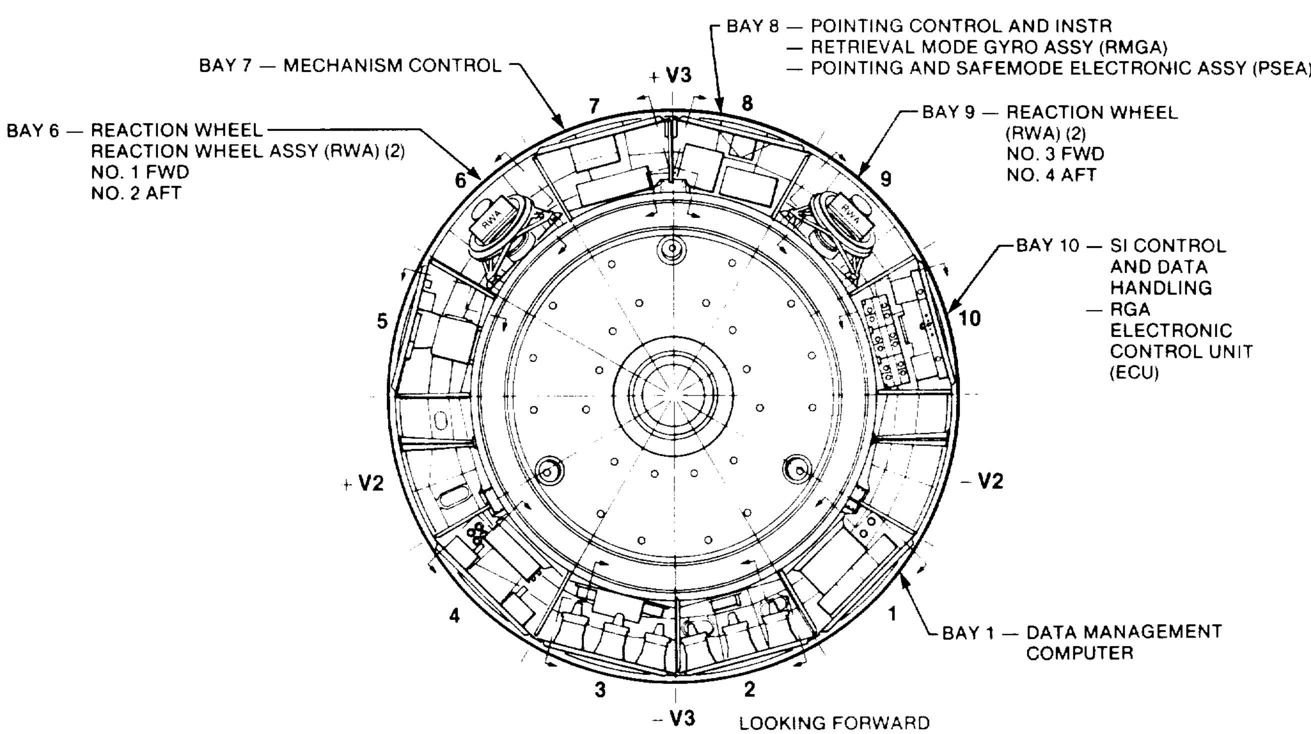


Figure 2–14 Location of the PCS Equipment

within its field of view. The three trackers are located below the focal plane structure, on the -V3 axis, next to the rate sensor units. The STOCC uses a star tracker as a calibration instrument when the Space Telescope maneuvers into its initial orientation. The trackers also calculate position information before and after coarse positioning to help the fine guidance sensors lock onto guide stars. The trackers interact with the fine guidance sensors and the rate gyros, at a command from STOCC, to provide a reference for targeting. See Figure 2-15 for detail on the star trackers.

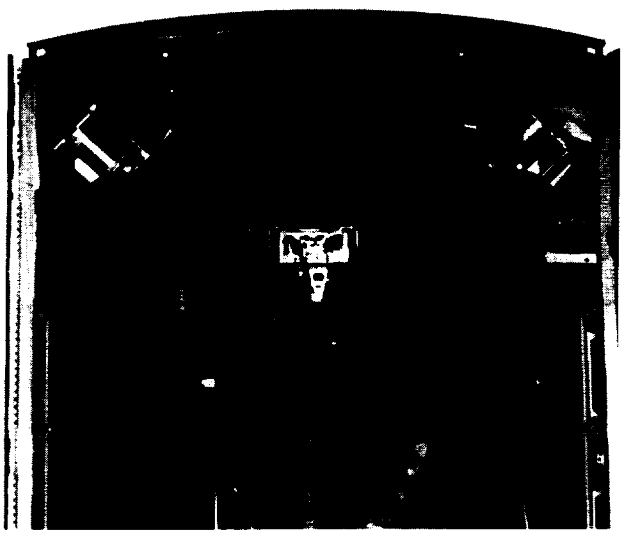


Figure 2-15 FHST Detail (Aft Shroud Door Open)

The three fine guidance sensors, discussed in more detail later, measure the angular position of a star. They make the most delicate fine pointing adjustments, accurate to within a fraction of an arcsecond, to pinpoint the target. Two of the guidance sensors perform guide-star pointing, while the third is available for positional measurement of specific stars, called astrometry. This function is discussed in Chapter 3.

2.1.4.2 PCS Computer. The pointing control subsystem uses the DF-224 computer in the data management subsystem to calculate position updates. The DF-224 translates ground targeting commands into reaction wheel operations that maneuver the spacecraft. The computer offsets the reaction wheel momentum with magnetic torque. The DF-224 also smooths HST movement to minimize the effects of vibration on telescope optics.

2.1.4.3 Actuators. The PCS has two types of actuators, reaction wheel assemblies and magnetic torquers, which move the spacecraft into commanded positions.

The four reaction wheel assemblies use spin momentum to move the HST into position. The wheels also maintain the spacecraft in a stable position. They work by rotating a large flywheel up to 3000 rpm and braking it to transfer momentum to move the spacecraft. The wheel axes are oriented so that the HST can operate with only three wheels, if required. The wheel assemblies are paired, two each in bays 6 and 9 of the SSM equipment section. Each wheel is 23 in. (59 cm) in diameter and weighs about 100 lb (45 kg). See Figure 2-16 for the configuration of the reaction wheel assemblies.

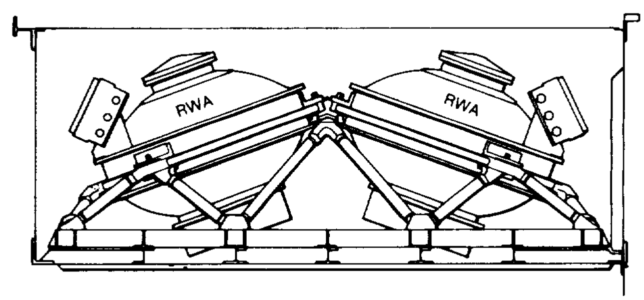


Figure 2-16 Reaction Wheel Assembly

The magnetic torquers create torque to change the reaction-wheel speed. The torquers react against the earth's magnetic field. The torque reaction occurs in the direction that reduces the reaction-wheel speed by balancing the momentum. The torquers provide torque in directions perpendicular to the earth's magnetic field lines.

The torquers also act as a backup system, when the HST stabilizes its initial orbital attitude, and during a system failure. Each torquer, located externally on the forward shell of the SSM, is 8.3 ft (2.5 m) long, 3 in. (8 cm) in circumference, and weighs 100 lb (45 kg).

2.1.4.4 PCS Operation. To point precisely, the pointing control subsystem combines the actions of the gyros, reaction wheels and torquers, star trackers, and fine guidance sensors. The fine guidance sensors provide a reference point from which the Space Telescope can begin repositioning. The STOCC commands the reaction wheels to spin, accelerating or decelerating as required to rotate the HST toward a new target. The rate gyros sense the HST's vehicular motion and provide short-term attitude updates to assist fine pointing and spacecraft maneuvers. If needed, the magnetic torquers can unload the reaction-wheel speed.

As the HST nears the target area, the star trackers locate preselected guide stars, which stand out brightly in that region of the sky. Once the spacecraft has the guide stars within a target area about 60 arcmin^2, the two fine guidance sensors take over pointing duties. Working with the gyros and reaction wheels to adjust the precise pointing, the guidance sensors point the HST to within 0.01 arcsec of the target. The pointing control system can maintain this position, wavering no more than 0.007 arcsec, for up to 24 hours to guarantee a faint-object observation exposure time totaling 10 cumulative hours.

2.1.5 Electrical Power Subsystem

Electrical power for the HST and the scientific instruments comes from the electrical power subsystem. The major components are the two solar array wings and their electronics, six batteries, six charge current controllers, one power control unit, and four power distribution units. All except the solar arrays are located in the bays around the equipment section.

Before the Space Telescope is placed into orbit, the Space Shuttle, and later the on-board HST batteries, provide enough power to deploy the HST. Then the solar arrays are extended and begin converting solar radiation into electricity. This is stored in the batteries and distributed by the power control and power distribution units. The array electronics, the SSM, the OTA, the SI C&DH, and all scientific instruments receive their power from this subsystem (see Figure 2-17).

2.1.5.1 Solar Arrays. The solar array panels, discussed more thoroughly later in this chapter, are the major source of electrical power. Each array wing has a solar cell blanket to assimilate the sun's energy. The electricity produced by the solar cells charges the HST batteries.

Each array wing has an electronics control assembly. This consists of a solar array drive electronics unit, which transmits positioning commands to the wing assembly, and a deployment control electronics unit, which controls the drive motors extending and retracting the wings.

2.1.5.2 Batteries and Charge Current Controllers. The six nickel-hydrogen batteries provide backup power when the HST is within the earth shadow and the solar arrays are eclipsed. When fully powered, each battery can produce a maximum of 68 amp-hours. This is enough power to supply the HST and its major systems for greater than 3.5 hours after switching to battery power before the solar arrays must be used as a power source.

The solar arrays recharge the batteries. Power is processed through a charge current controller, one per battery. Each charge current controller also provides a voltage-temperature control for the charging battery.

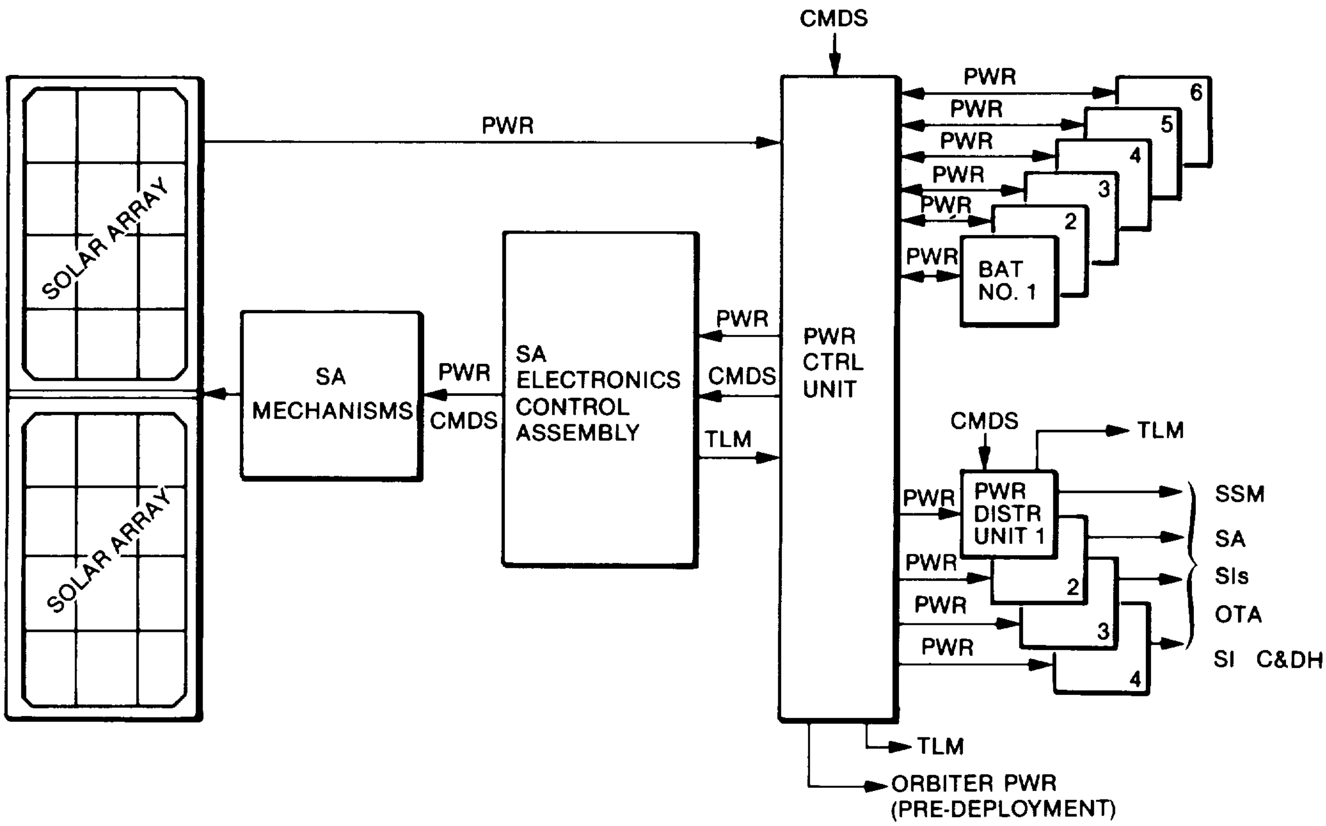


Figure 2–17 Electrical Power Subsystem

The batteries are 520 lb (236 kg) for three batteries and consist of 23 cell plates inside an aluminum casing. The batteries are attached to the doors of equipment section bays 2 and 3, in groups of three (see Figure 2-18).

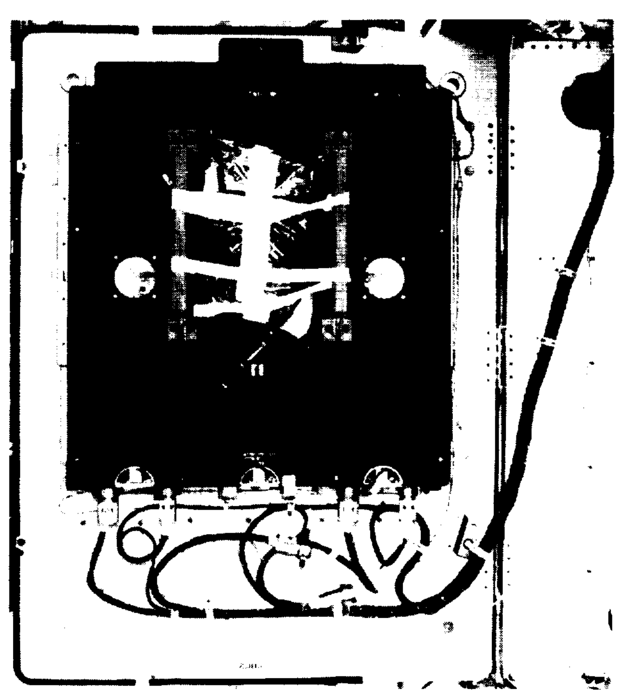


Figure 2–18 Nickel-Hydrogen Battery

2.1.5.3 Power Control and Distribution Units. The power control unit interconnects and switches electricity flowing between the solar arrays, batteries, and charge current controllers. The power control unit provides the main power line to the four power distribution units. The power control unit weighs about 120 lb (55 kg), measures 43 x 12 x 8 in. (109 x 30 x 20 cm), and is located in bay 4 of the equipment section.

The four power distribution units, located on the inside of the door to bay 4, contain the power lines, switches, fuses, and monitoring devices leading to the rest of the HST. Two units are dedicated to the OTA, scientific instruments, and SI C&DH; two supply the SSM. Each distribution unit measures about 10 x 5 x 18 in. (25 x 12.5 x 45 cm) and weighs 25 lb (11 kg).

2.1.6 Thermal Control

The overall HST thermal plan uses passive, energy-conserving controls, such as multi-layer insulation (MLI) covering 80% of the HST exterior, and supplemental electric heaters, to maintain temperatures. The insulation blankets have 15 layers of aluminized Kapton, with an outer layer of aluminized Teflon Flexible Optical Solar Reflector (FOSR). Aluminized or silverized FOSR tape covers most of the remaining exteriors. These coverings protect against the cold of space and reflect solar heat. Other passive techniques include using reflective or absorptive paints and venting areas where heat builds up.

The SSM thermal control subsystem maintains temperatures within set limits for the components mounted on the SSM equipment section and structures interfacing with the OTA and SIs. The subsystem will maintain component temperatures even for "worstcase" events like environmental fluctuations, passage from "cold" earth shadow to "hot" solar exposure during each orbit, and heat generated from equipment operation.

Specific thermal-protection features of SSM include:

- MLI thermal blankets for the light shield and forward shell
- Aluminum (AL) FOSR tape on the aperture-door surface facing the sun
- Specific patterns of FOSR and MLI blankets on the exteriors of the equipment section bay doors, with internal MLI blankets on the bulkheads to maintain thermal balance between bays
- Efficient placement of equipment and use of bay space to match temperature requirements, such as placing heat- dissipating equipment on the side of the equipment section most in orbit shadow
- Silverized (AG) FOSR tape on the aft shroud and aft bulkhead exteriors
- Radiation shields inside the aft shroud doors, and MLI blankets on the aft bulkhead and shroud interiors to protect the scientific instruments
- Over 200 temperature sensors placed throughout the SSM, externally and internally, to monitor individual components and control heater operations

Figure 2-19 shows the location of thermal protection on the SSM, with symbols indicating the type of protection used.

2.1.7 Safing (Contingency) System

The Hubble Space Telescope design includes overlapping and redundant equipment to safeguard against any breakdown in orbit. Nonetheless, a contingency or safing system exists for emergency operations. It uses many of the pointing and data-management components, as well as dedicated hardware called the pointing safemode electronics assembly. This system is designed to maintain the Space Telescope's attitude, move the solar arrays to get maximum sun exposure, and conserve electrical power by minimizing power drains. The safing system can operate the spacecraft with no communications link to ground control for up to 72 hours. Within that time, it is assumed, the STOCC would recontact the HST, analyze any problem that occurred to cut off communications, and correct the problem.

The safing system automatically monitors the HST on-board functions in Monitor Mode, which the STOCC can turn on and off or override. The system sends "keep-alive" signals that indicate all Space Telescope systems are functioning. If the safing system alerts ground

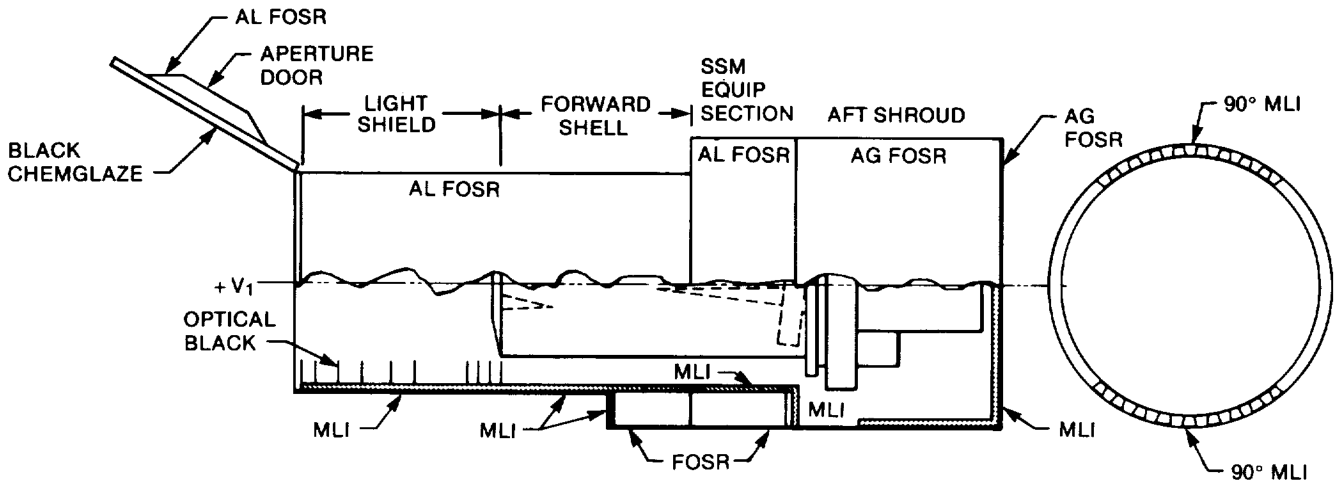


Figure 2-19 Placement of Thermal Protection on SSM

control to a problem, the STOCC will call in a special failure investigation team to evaluate the problem while the safing system maintains control.

The investigation team will classify the problem as a data or flight problem. If spacecraft data produced inconsistencies or errors, this would be classified as a data problem. If a flight system such as an electrical unit deviated from expected performance, this would be classified as a flight problem. The failure investigation team then will indicate the probable cause, list the subsystems and components involved, and recommend how to correct the problem.

If possible, the STOCC will adjust the Space Telescope from the ground to solve the problem. If the situation continues or worsens, the STOCC may consider an unplanned maintenance mission.

Meanwhile, the safing system will follow a progression of contingency operating modes depending upon the situation aboard the Space Telescope. If a malfunction occurs and does not threaten the HST's survival, the safing system initially will move into Software Inertial Hold Mode. The system will hold the HST in the last position commanded. If a maneuver is in progress, the safing system will complete the maneuver, then hold the HST in that position. It will suspend all science operations until the malfunction is corrected.

If the system detects a marginal electrical power problem, or an internal pointing control subsystem safety check fails, the HST will enter Software Sun Point Vehicle Mode. The safing system will maneuver the telescope so the solar arrays point toward the sun to generate constant solar power. HST equipment will remain within operating temperatures and above survival temperatures, anticipating a return to normal operations. The STOCC must intercede to repair the malfunction before any science operations or normal functions can be resumed.

To this point, the safing system will be operating through computer software. If conditions worsen, the system will turn over control to the pointing safemode electronics assembly (PSEA), under Hardware Sun Point Mode. Problems that could provoke this action include any of the following:

- A computer malfunction
- Batteries losing more than 50% of their charge
- Two of the three rate gyro assemblies failing
- The data management subsystem failing

If these conditions occur, the safing system will stop sending the "keep-alive" signals.

In Hardware Sun Point Mode the PSEA computer will command the HST and turn off selected equipment to conserve power. Shut-down components could include the DF-224 computer and, if the emergency continues for two hours, the SI C&DH unit. A payload safing sequence will begin, and, if not already done, the Space Telescope will turn to face the solar arrays toward the sun, guided by the coarse sun sensors. If the situation is not reversed quickly, the safemode assembly begins removing power from equipment not required for the HST's survival. Recovery from this situation is a lengthy process involving STOCC analysis.

The Space Telescope can maintain this condition for over 72 hours without any contact from the STOCC. But if contact and repair are delayed beyond a reasonable time, if more HST systems fail, or if the PSEA cannot continue the operations listed above, the spacecraft enters Contingency Gravity Gradient Mode. This keeps the HST in a gravitationally-stable orbital attitude until the Space Shuttle can retrieve it. The PSEA computer uses the retrieval mode gyro assembly to maneuver into a survival orbit, adjusted only by magnetic torquers. The STOCC again must evaluate whether the mission should be discontinued and the HST brought to earth for major repair. See the chart in Figure 2-20 for a diagram of the safing system progression.

2.1.7.1 PSEA and RMGA. The pointing safemode electronics assembly consists of 40 electronic printed-board circuits with redundant electronics to run the HST even in the case of internal assembly failure. It weighs 86 lb

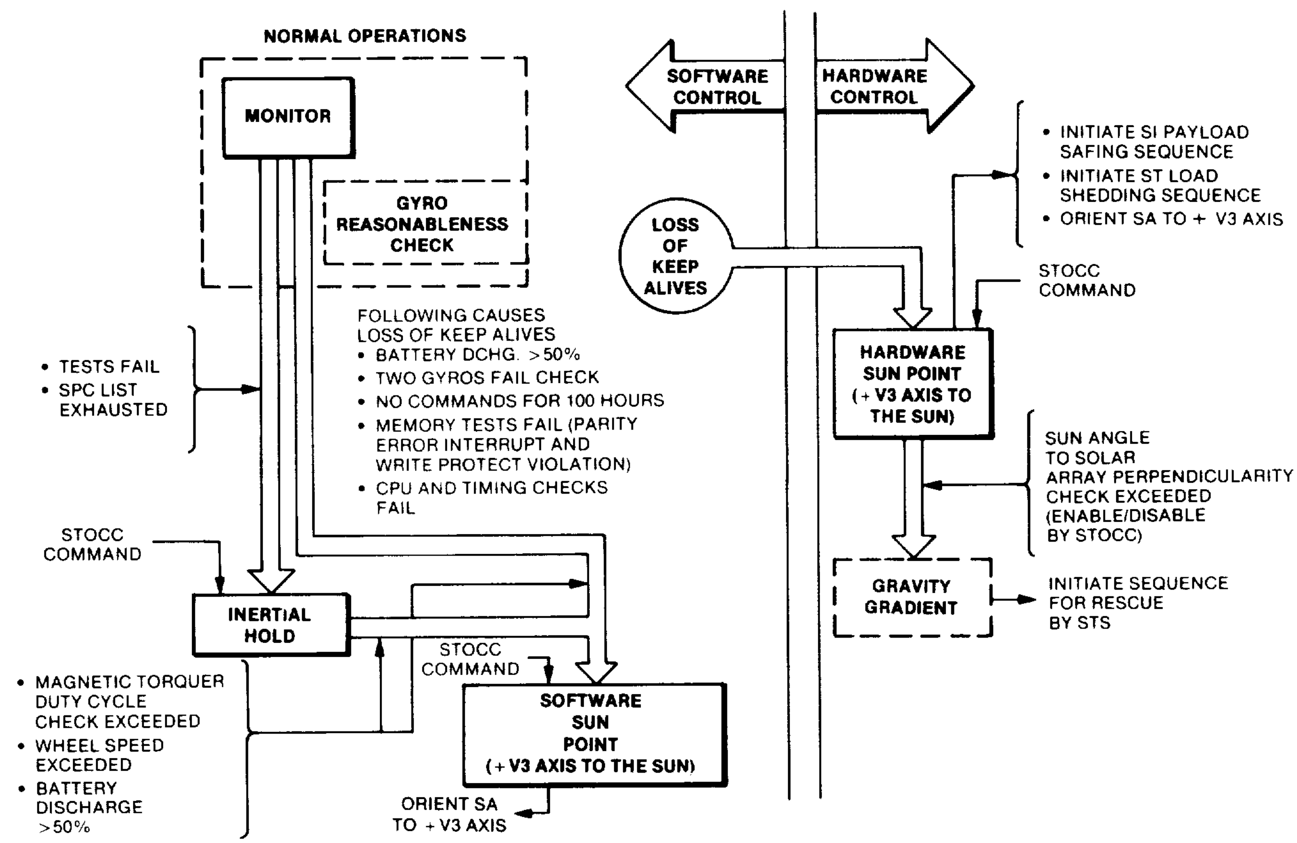


Figure 2–20 Safing System Progression

(39 kg) and is installed in equipment section bay 8. The retrieval mode gyro assembly, also in bay 8, consists of three gyroscopes that are less precise than the rate gyros.

2.2 THE OPTICAL TELESCOPE ASSEMBLY

The Optical Telescope Assembly (OTA) was designed and built by the Perkin-Elmer Corporation. Modest in size by ground- based observatory standards, and of a straightforward optical design, the accuracy with which the telescope assembly has been built, coupled with its place above the earth's atmosphere, render its performance superior.

As is common practice in the design of large telescopes, the OTA uses a "folded" design, which enables a long focal length of 189 ft (57.6 m) to be packaged into a small telescope length of 21 ft (6.4 m). (Several smaller mirrors in the scientific instruments also use this design to lengthen the light path within the particular scientific instrument.) This form of telescope is called a Cassegrain, and its compactness is an essential ingredient of an observatory designed to fit inside the Space Shuttle payload bay.

Conventional in optical design, the OTA is unconventional in every other respect. Large telescopes at ground-based sites are limited in their performance by the resolution attainable by operating under the earth's atmosphere. But the Space Telescope will orbit high above the atmosphere and provide an unobstructed view of the universe. This is why the OTA was designed and built with exacting tolerances to provide near-perfect image quality over the broadest possible region of the spectrum.

The OTA is a variant of the Cassegrain, known as a Ritchey Chretien, in which both the mirrors are hyperboloidal[1] in shape. This form is completely corrected for coma[2] and spherical aberrations to provide what is known as an aplanatic[3] system. The only residual aberrations are field curvature and astigmatism. Both of these are zero exactly in the center of the field and increase toward the edge of the field. These aberrations are easily corrected within the instrument optics. For example, in the Faint Object Camera there is a small telescope designed to remove the image astigmatism.

Figure 2-21 shows the path of a light ray from a distant star as it travels through the telescope to the focus. Light travels down the tube, past baffles which attenuate reflected light from unwanted bright sources, to the 94.5-in. (2.4 m) primary mirror. Reflecting off the front surface of the concave mirror, the light bounces back up the tube to the 12-in. (0.3 m) diameter convex secondary mirror. The light is now reflected and converged through the 23.5-in. (60 cm) hole in the primary mirror, to the telescope focus, 3.3 ft (1.5 m) behind the primary mirror.

The focal plane is shared between five scientific instruments and three fine guidance sensors by a system of mirrors. In the very center of the field of view is a small "folding" mirror which directs light into the Wide Field/Planetary Camera. The remaining "science" field is divided between four axial scientific instruments, each receiving a quadrant of the circular field of view. Around the outside portion of the "science" field, the "guidance" field is divided among the three fine guidance sensors by their own "folding" mirrors. Each FGS receives 60 square arcmin of field in a 90-degree sector. See

[1] "Hyperboloidal" refers mathematically to the shape of the mirror. A hyperboloidal mirror has a slightly deeper curvature than a parabolic mirror.

[2] "Coma" are aberrations in the image that give it a "tail".

[3] Corrected everywhere in the field of view.

Figure 2-22 for the instrument/sensor fields of view.

The Optical Telescope Assembly is a "host" to the scientific instruments and fine guidance sensors in that it maintains the structural support and optical-image stability required for these instruments to fulfill their functions. The components of the OTA are the primary mirror assembly, the secondary mirror assembly, the focal plane structure assembly, and the OTA equipment section. All assembly systems are designed and built by Perkin-Elmer; LMSC built the equipment section (see Figure 2-23).

2.2.1 Primary Mirror Assembly

The primary mirror assembly is made up of the mirror itself supported inside the main ring, which is the structural backbone of the telescope, and the main and central baffles. This assembly provides the structural coupling to the rest of the spacecraft, through a set of kinematic attachment brackets linking the main ring to the Support Systems Module. The assembly also provides support to the primary mirror and the OTA baffles. It has the following major parts:

- The primary mirror
- Main ring structure
- Reaction plate and actuators
- Main and central baffles

These parts are pictured in Figure 2-24.

2.2.1.1 Primary Mirror. The primary mirror blank is a product of Corning Glass Works that is known as ultra-low-expansion (ULE) glass. It was chosen for its very low expansion coefficient, which assures the telescope minimum sensitivity to temperature changes. The mirror is a "sandwich" construction in which two lightweight facesheets are separated by a core, or filling, of glass honeycomb ribs in a rectangular grid (see Figure 2-25). This construction results in an 1800-lb (818-kg) mirror instead of a solid-glass mirror weighing 8000 lb.

The mirror blank, 8 ft. (2.4 m) in diameter, was ground to shape by Perkin-Elmer (P-E), in P-E's

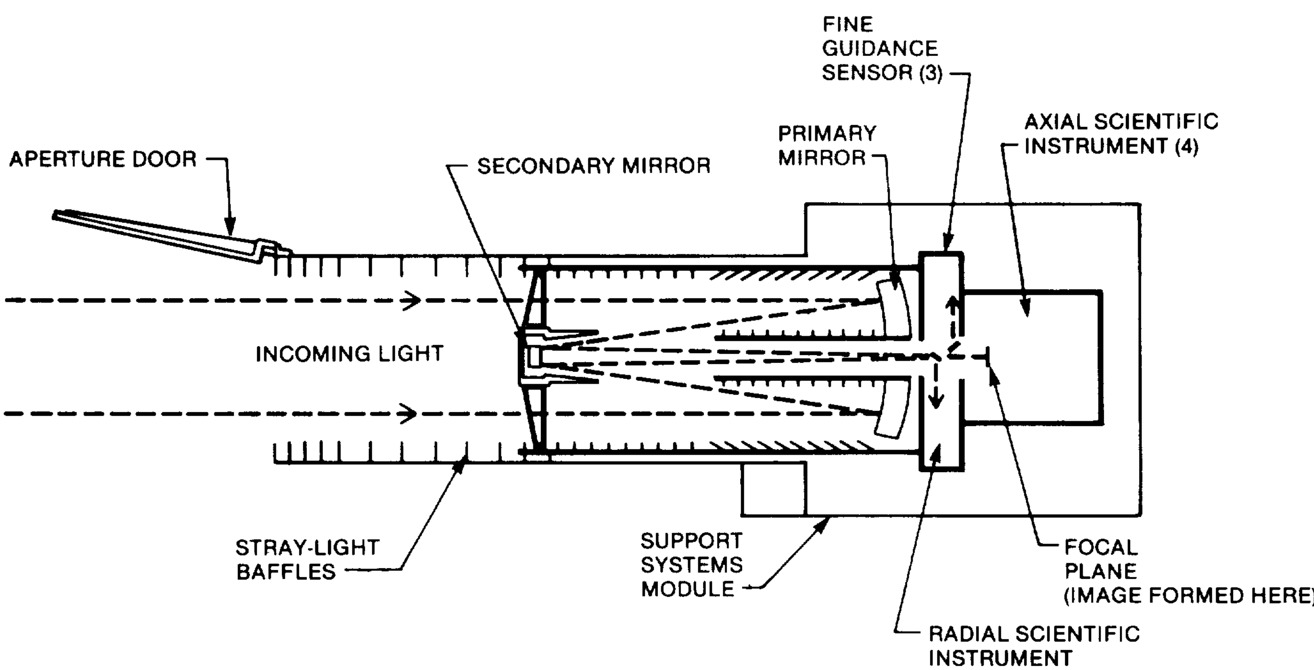


Figure 2-21 Light Path, Main Telescope

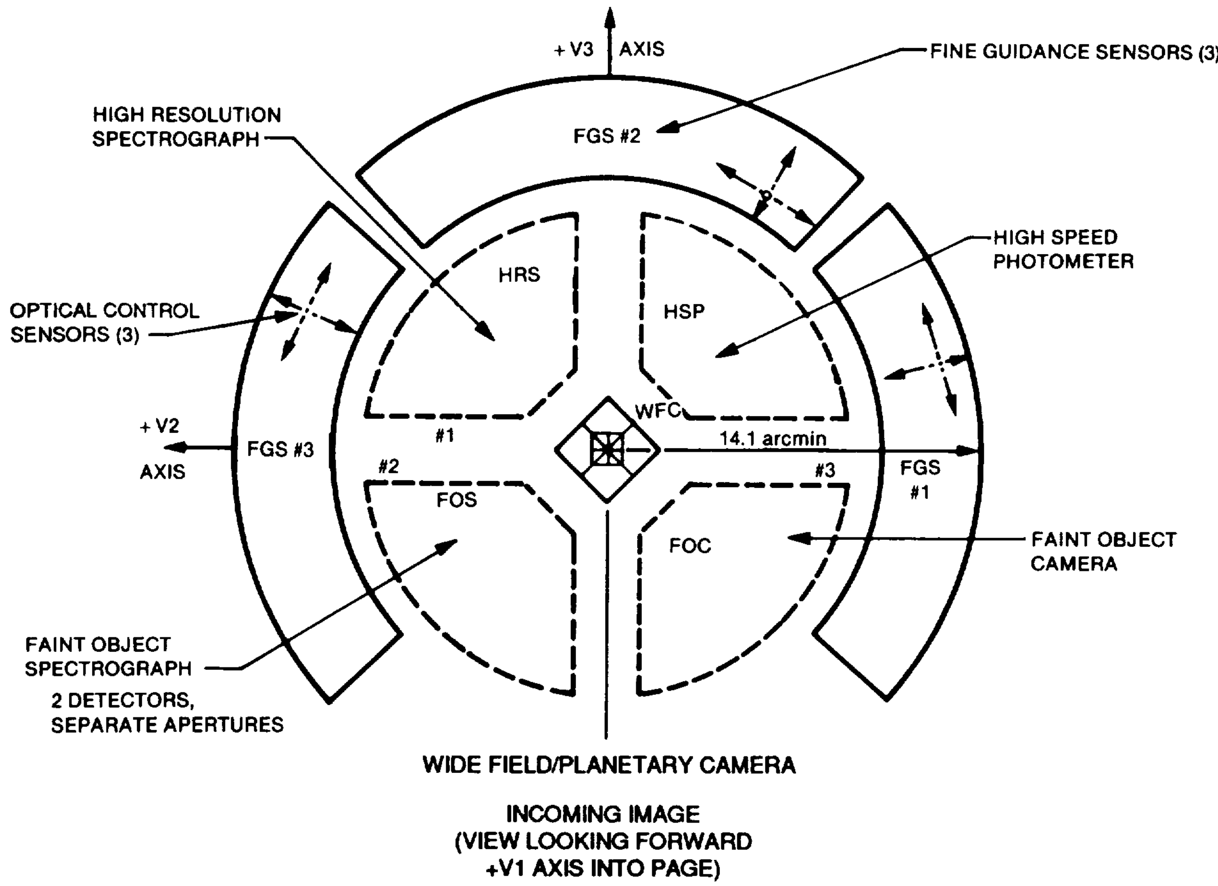


Figure 2-22 Fields of View, Instruments/Sensors

large optics fabrication facility. Once it was close to its final hyperboloidal shape, it was transferred to P-E's computer-controlled polishing facility. Here the mirror was polished to its final surface quality. The largest deviation from perfection anywhere on the surface of the mirror is less than half a millionth of an inch. If the primary mirror was the size of the United States, the highest mountain or deepest valley would deviate less than two inches from the surface.

After being ground and polished, the glass surface was coated with a reflective layer of aluminum and a protective layer of magnesium fluoride, only 0.1 and 0.025 micrometers thick, respectively. The fluoride layer protects the aluminum from oxidation and enhances reflectance at the important hydrogen emission line known as Lyman-Alpha. The reflective quality of the mirror is better than 70% at 1216 angstroms (Lyman-Alpha), in the ultraviolet spectral range, and over 85% for visible light. Figure 2-26 shows the primary mirror.

The primary mirror is mounted to the main ring through a set of kinematic linkages. The linkages attach to the mirror by three rods that penetrate right through the glass, for axial constraint, and also by three pads bonded to the back of the glass for lateral support.

2.2.1.2 Main Ring. The main ring structure encircles the primary mirror; supports the mirror, the main baffle and central baffle, and the metering truss; and integrates the elements

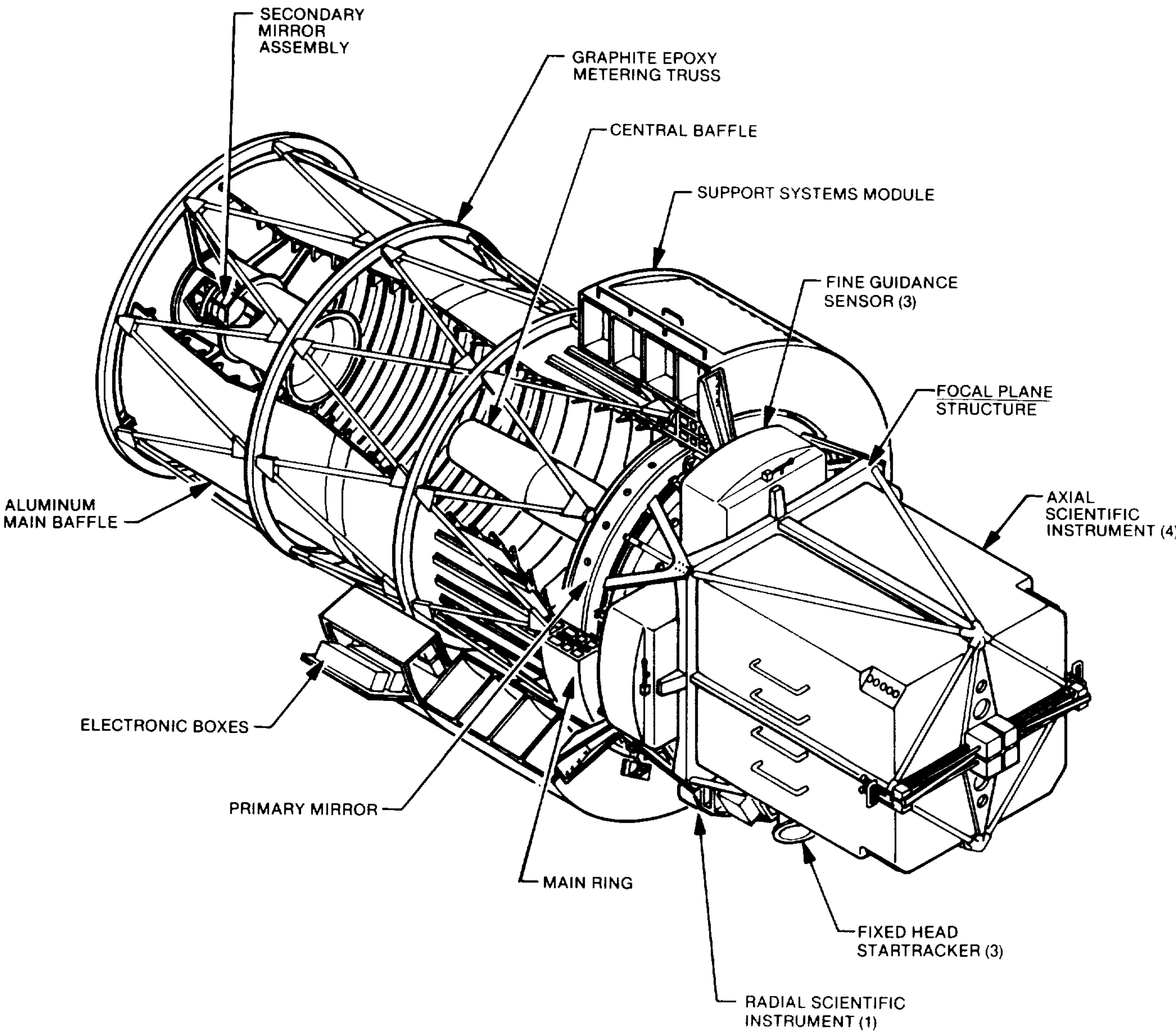


Figure 2–23 OTA Components

of the telescope to the spacecraft. The ring, made of titanium, is a hollow box beam 15 in. (38 cm) thick, weighs 1200 lb (545.5 kg), and has an outside diameter of 9.8 ft (2.9 m) (see Figure 2-27). It is suspended inside the SSM by a kinematic support.

2.2.1.3 Reaction Plate. The reaction plate structure is a wheel of I-beams forming a bulkhead behind the main ring, spanning its diameter. It radiates out from a central ring, which supports the central baffle. Its primary function is to carry an array of heaters, which radiate warmth to the back of the primary mirror, maintaining its temperature at 70 degrees. Made of beryllium of light weight and stiffness, the plate also supports a set of 24 figure-control actuators attached to the primary mirror and arranged around the reaction plate in two concentric circles. These can be commanded from the ground, if necessary, to make small corrections to the shape of the mirror.

2.2.1.4 Baffles. The baffles of the OTA prevent stray light from bright objects, such as the sun, moon, and earth, from reflecting down the telescope tube to the focal plane. The primary mirror assembles includes two of the three OTA baffles.

Attached to the front face of the main ring, the outer, main baffle is an aluminum cylinder, 9 ft (2.7 m) in diameter and 15.7 ft (4.8 m) long. It is equipped with fins internally to help attenuate stray light. The central baffle is 10 ft (3 m) long, conical in shape, and attached to the reaction plate through a hole in the center of the primary mirror. It extends down the centerline of the telescope tube. The baffle interiors were painted with flat black paint to minimize light reflection.

2.2.2 Secondary Mirror Assembly

The secondary mirror assembly cantilevers off the front face of the main ring and supports the secondary mirror at exactly the correct position in front of the primary mirror. This position must be accurate within a tenth of one-thousandth of an inch whenever the telescope is operating. The assembly is composed of the mirror subassembly, a light baffle, and an outer graphite-epoxy metering truss support structure (see Figure 2-28).

The secondary mirror subassembly contains the mirror, which is mounted on three pairs of alignment actuators controlling the position and orientation of the mirror. All are enclosed within the central hub at the forward end of the truss support.

PRIMARY MIRROR ASSEMBLY

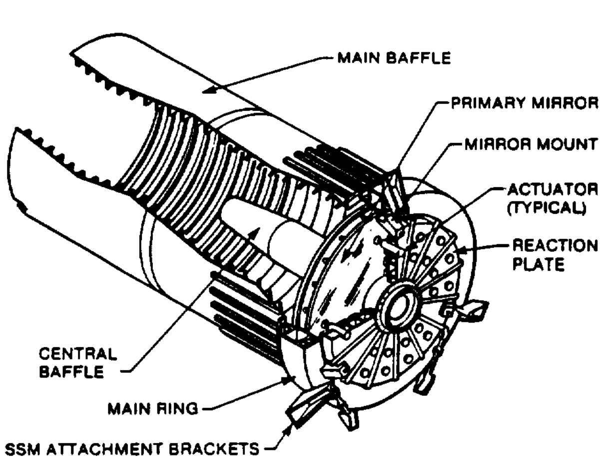
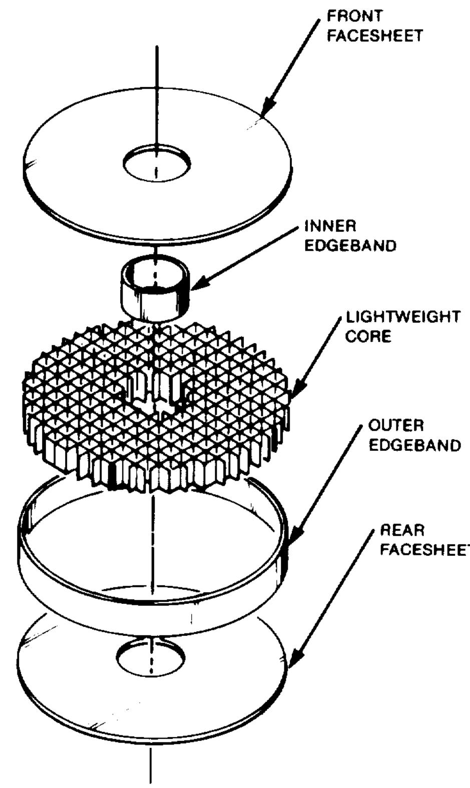


Figure 2-24 The Primary Mirror Assembly

MIRROR CONSTRUCTION



(THE MIRROR IS MADE OF CORNING CODE 7971 ULE—ULTRA-LOW EXPANSION—SILICA GLASS)

Figure 2-25 Primary Mirror Construction

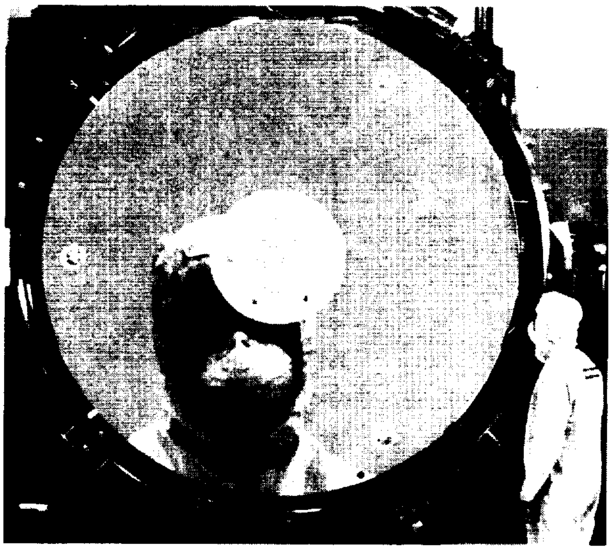


Figure 2-26 Primary Mirror

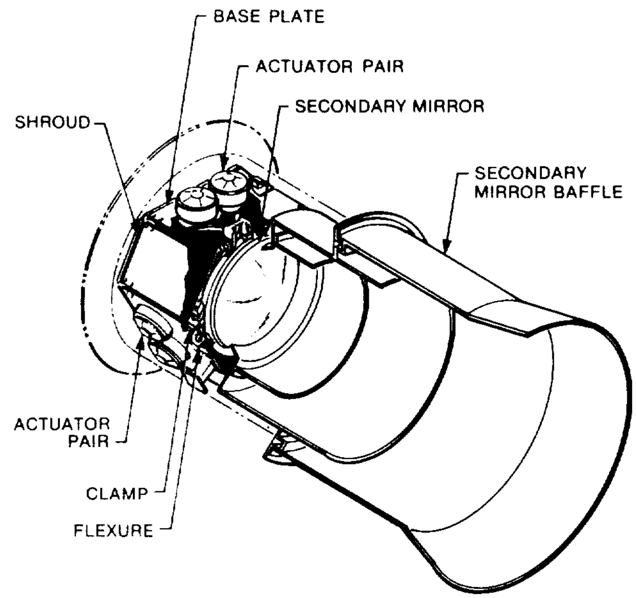


Figure 2-28 Secondary Mirror Assembly

The secondary mirror has a magnification of 10.4X, converting the primary-mirror converging rays from f/02.35 to a focal ratio system prime focus of f/24 and sending it back toward the center of the primary mirror, where it passes through the central baffle to the focal point. The mirror itself is a convex hyperboloid, 12 in. (0.3 m) in diameter, and is made from Zerodur glass coated with aluminum and magnesium fluoride. It is steeply convex and its surface accuracy is even greater than the primary mirror.

The actuators can be adjusted by ground command to align the secondary mirror in just the right position to provide perfect image quality. The adjustments are calculated from data picked up by the optical control system's tiny sensors located in the fine guidance sensors.

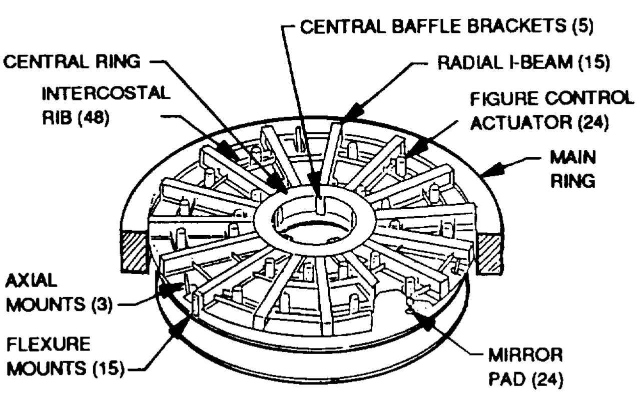


Figure 2-27 The Main Ring and Reaction Plate

The principal structural element of the secondary mirror assembly is the metering truss, a cage with 48 latticed struts attached to three rings and a central support structure for the secondary mirror. The truss, 16 ft (4.8 m) long and 9 ft (2.7 m) in diameter, is a graphite fiber-reinforced epoxy structure. Graphite was chosen for its high stiffness, light weight, and because it reduces the structure's expansiveness to nearly zero. This is vital because the secondary mirror must stay perfectly placed relative to the primary mirror, accurate to within 0.0001 in. (2.5 micrometers) when the telescope operates.

The truss is attached at one end to the front face of the main ring of the primary mirror assembly. The other end has a central hub which houses the secondary mirror and baffle along the optical axis. Aluminized mylar multi-layer insulation (MLI) material in the truss compensates for temperature variations of up to 30 degrees Farenheit when the HST is in earth shadow so the primary and secondary mirrors remain aligned. See Figure 2-29 for detail on the truss support structure.

The conical secondary mirror subassembly light baffle extends almost to the primary mirror. It reduces the stray bright-object light from bright sources outside the HST field of view.

2.2.3 Focal Plane Structure Assembly

The focal plane structure (FPS) is a large optical bench which aligns the image focal plane of the HST with the scientific instruments and fine guidance sensors and physically supports the SIs and FGSs. The -V3 side of the structure, away from the sun in space, supports the fixed-head star trackers and rate sensing units (see Figure 2-30). It also provides the facilities for in-orbit replacement of any of the instruments and thermal isolation between each instrument.

The structure is 7 ft (2.1 m) square by 10 ft (3.04 m) long and weighs over 1200-lb (545.5 kg). It is made from graphite-epoxy, augmented with mechanical fasteners and metallic joints at strength-critical locations, because it must have extreme thermal stability and be stiff, lightweight, and strong. The FPS has metallic mounts and supports for orbital replaceable units used during maintenance.

The focal plane structure cantilevers off the aft face of the main ring, attached at eight flexible points that adjust to eliminate thermal distortions. The structure provides a fixed alignment for the fine guidance sensors. It has guide-rails and latches at each instrument mounting location so Orbiter crews can exchange scientific instruments and other equipment easily in orbit.

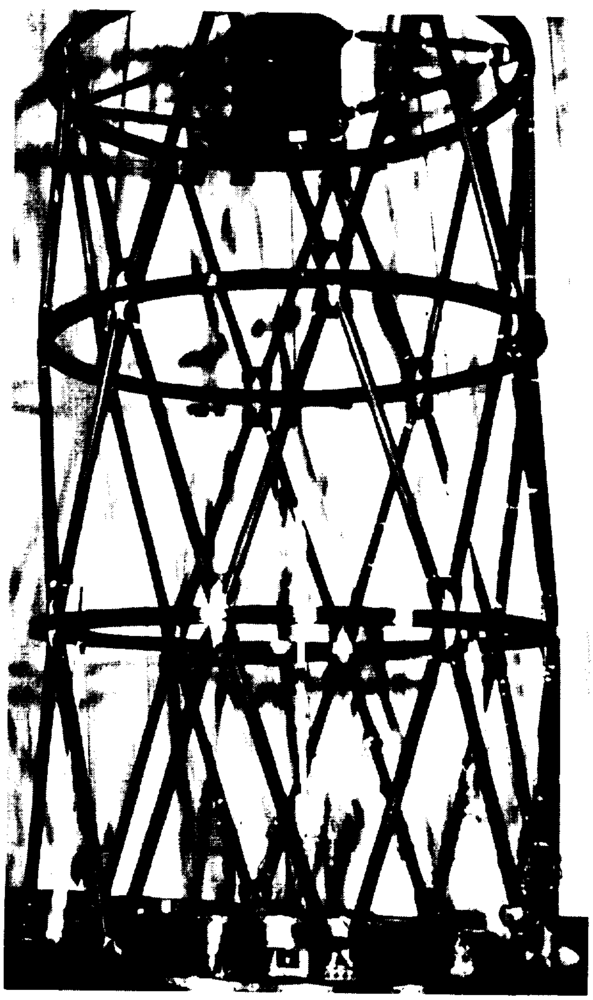


Figure 2-29 Mirror Metering Truss Structure

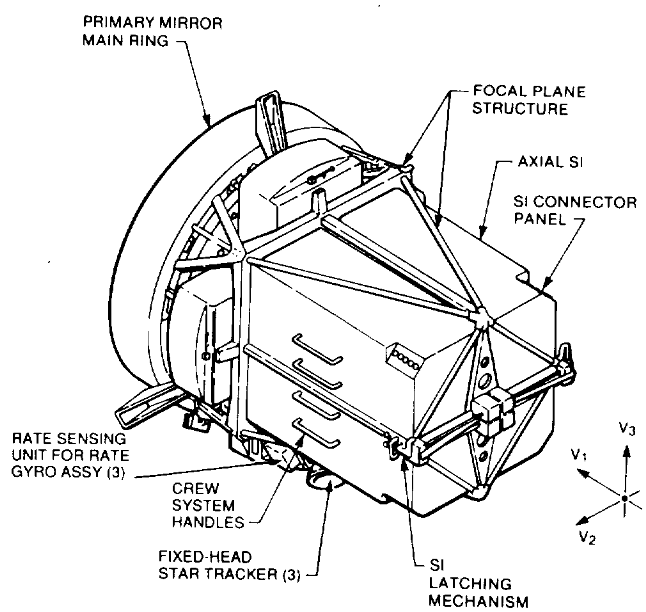


Figure 2-30 Focal Plane Structure

2.2.4 OTA Equipment Section

The equipment section for the Optical Telescope Assembly is a large semicircular set of compartments mounted outside the spacecraft on the forward shell of the SSM (see Figure 2-31). It contains the OTA electrical power/thermal control electronics system, the fine guidance electronics, actuator control electronics, optical control electronics, and the fourth DMS data interface unit. The OTA equipment section has nine bays; seven are used for equipment storage, two for support. All bays have outward-opening doors for easy access, cabling and connectors for the electronics, and heaters and insulation for thermal control.

The electrical power/thermal control electronics (EP/TCE) system distributes power from the SSM electric power subsystem to the OTA systems. The temperature-control system uses thermostat controllers to regulate the mirror temperatures. This prevents mirror distortion from cold space temperatures. The EP/TCE also collects thermal sensor data for transmission to the ground.

The three fine guidance electronics (FGE) units provides power, commands, and telemetry to each fine guidance sensor. The electronics unit performs computations for the sensor and interfaces with the spacecraft pointing system for effective telescope line-of-sight pointing and stabilization. There is a guidance electronics assembly for each guidance sensor.

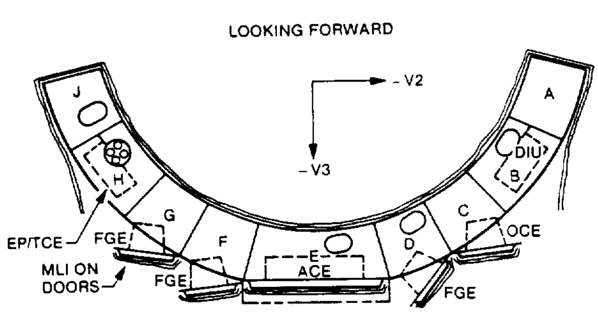


Figure 2-31 The OTA Equipment Section

The actuator control electronics (ACE) unit provides the command and telemetry interface to the 24 actuators attached to the primary mirror and six actuators attached to the secondary mirror. The ACE selects which actuator to move, and monitors its response to the command. Positioning commands go from the ground to the electronics through the data interface unit.

The optical control electronics (OCE) unit controls the optical control sensors. These are white light interferometers which measure the optical quality of the OTA and send the data to the ground for analysis. There is one OCS for each FGS, but all OCSs are controlled by the OCE.

The data interface unit (DIU) is an electronic interface between the other OTA electronics units and the HST command and telemetry system.

2.3 FINE GUIDANCE SENSORS

The three fine guidance sensors (FGSs) are located at 90-degree intervals around the circumference of the focal plane structure, between the structure frame and the main ring (see Figure 2-30). Each sensor is 5.4 ft (1.5 m) long, 3.3 ft (1 m) wide, and weighs 485 lb (220 kg). Perkin-Elmer made the sensors.

Each FGS enclosure — sometimes called a radial bay module — actually houses a guidance sensor and a wavefront sensor. The wavefront sensors are elements of the OCS, which are used to align and optimize the optical system of the telescope.

The ability of the HST to remain pointing at a distant target to within 0.007 arcsec for long periods of time is due largely to the accuracy of the FGSs. The guidance sensors lock on a star and measure any apparent motion to an accuracy of 0.0028 arcsec. That is equivalent to seeing from New York City the motion of a landing light on an aircraft flying over San Francisco.

When two sensors lock on a target, the third can measure the angular position of a star, a process called astrometry. The astrometric function of the sensors is discussed in Chapter 3.

2.3.1 FGS Composition and Function

The fine guidance sensors consist of a large structure housing a collection of mirrors, lenses, servos to locate the image, prisms to fine-track the image, beam splitters, and four photomultiplier tubes. The entire mechanism makes the adjustment required to move the HST into precise alignment with a target star. Each sensor has a large (60 armin^2) field of view to search for and track stars, and a 5.0 arcsec-squared field of view used by the detector prisms to pinpoint the star.

The fine guidance sensors work in pairs to aim the Space Telescope. The Guide Star Selection System, developed by the Science Institute, catalogs and charts guide stars near each observation target to make it easier to find the target. First one sensor will search for a target guide star. After the first sensor locks on a guide star, the second sensor locates and locks on another target guide star. The guidance stars, once designated and located, keep the image of the observation target in the aperture of the selected scientific instrument.

Each fine guidance sensor uses a 90-degree sector of the telescope's field of view outside the central "science" field. This region of the field of view has the greatest astigmatic and curvature distortions. The size of the FGS field of view was chosen to heighten the probability of finding an appropriate guide star, even in the direction of the lowest star population — near the galactic poles.

An FGS "pick-off" mirror intercepts the incoming stellar image and projects it into the sensor's large field of view. Each FGS FOV has 60 square arcminutes available. The guide star of interest can be anywhere within this field, so the FGS will "look" anywhere in that field to find the star. Having found the star, the FGS has to "lock" onto it and send error signals to the HST telling how to move to keep the star image perfectly still.

The FGS can move its line of sight anywhere within its large FOV using a pair of star selector servos. Each may be thought of as an optical gimbal — one servo moves in a North-South direction; the other moves East-West. They steer the small FOV (5 arcsec^2) of the FGS detectors to any position in the whole FGS field. Encoders within each servo system send back the exact coordinates of the detector field centers at any point.

Since there is often some uncertainty about the exact location of the guide star in question, the star selector servos can also cause the detector to execute a search of the region around the most probable guide star position. It searches in a spiral pattern, starting at the center and spiraling out until the detector "finds" the guide star it seeks. Then the detectors are commanded to go into "fine-track" mode and hold the star image exactly centered in the field of view, while the star selector servo encoders send information about the position of the star to the spacecraft pointing control system.

The detectors themselves are a pair of interferometers called Koesters' prisms, coupled to photomultiplier tubes. Each detector operates in one axis, so two are needed. Operating on the incoming wavefront from the distant guide star, the interferometers compare the wave phase at one edge of the telescope entrance aperture with the phase at the opposite edge. When the phases are equal, the star is exactly centered. Any phase difference shows a pointing error which must be corrected.

Along the optical path from telescope to detector, there are additional optical elements which turn, or "fold," the beam in order to fit everything inside the FGS enclosure, and to correct the telescope's astigmatism and field curvature. All optical elements are mounted on a temperature-controlled graphite/epoxy composite optical bench.

Figure 2-32 is a simplified cutaway of the FGS; Figure 2-32b diagrams the optical path.

2.3.2 Wavefront Sensor

The optical control system is a system of three wavefront sensors and control actuators which enable ground controllers to correct and adjust the alignment of the telescope. They fit inside the FGS enclosure close to the pickoff mirror shown in Figure 2-32a.

The wavefront sensors are, like the FGS detectors, interferometers. These, however, are designed to measure small imperfections in the stellar wavefront result from its transit through the OTA. The imperfections contain information about the alignment of the secondary mirror, and the optical quality of the primary mirror. The data is telemetered to the ground and used to compute any corrections to the optical system. These corrections are converted into actuator commands and sent up to the HST to re-orient the OTA.

The wavefront sensors are very precise optical instruments and are mounted to a machined be-ryllium optical bench that is temperature-controlled, to maintain stability. Unlike the FGS sensors, which will be used constantly, the wavefront sensors will be used infrequently once the OTA has been aligned during the first month in space.

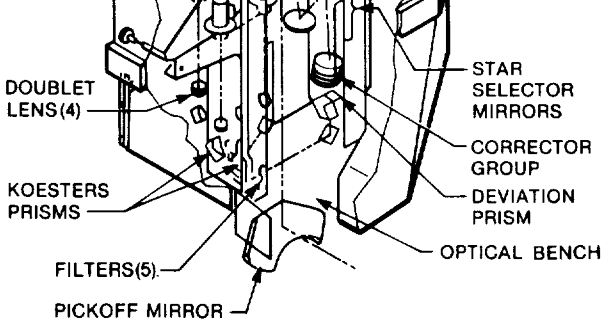


Figure 2-32a FGS Cutaway

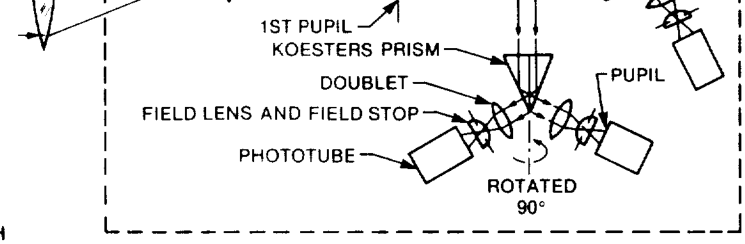


Figure 2-32b Optical Path, FGS

2.4 SOLAR ARRAYS

The two solar arrays, designed by the European Space Agency and built by British Aerospace, serve as the main source of power for the Hubble Space Telescope. The STOCC will operate the arrays, extending the panels and maneuvering the spacecraft to focus maximum sunlight on the arrays. The sunlight is converted to energy and stored in batteries until needed.

2.4.1 Configuration

The solar arrays are two rectangular wings of retractable solar cell blankets fixed between a two-stem frame. The blanket unfurls from a cassette in the middle of the wing. A spreader bar at each end of the wing stretches out the blanket and maintains tension.

The wings are on arms that connect to a drive assembly on the SSM forward shell at one end and to the cassette on the other end. The total length of the cassette, arm, and drive is 15.7 ft (4.8 m) (see Figure 2-33).

Each wing has ten panels, five on each half of the wing, that roll out from the cassette. The small panels are made up of 2,438 solar cells attached to a glass fiber/Kapton surface, with silver mesh wiring underneath that is covered by another layer of Kapton. The blankets are less than 500 micrometers thick so they can roll up tightly when the wings are stowed. Each wing weighs 17 lb (7.7 kg) and, at full extension, is 40 ft (12.1 m) long and 8.2 ft (2.5 m) wide.

2.4.2 Solar Array Subsystems

The subsystems for the solar arrays are the primary and secondary deployment mechanisms, the drive mechanism, and the electronic control assembly.

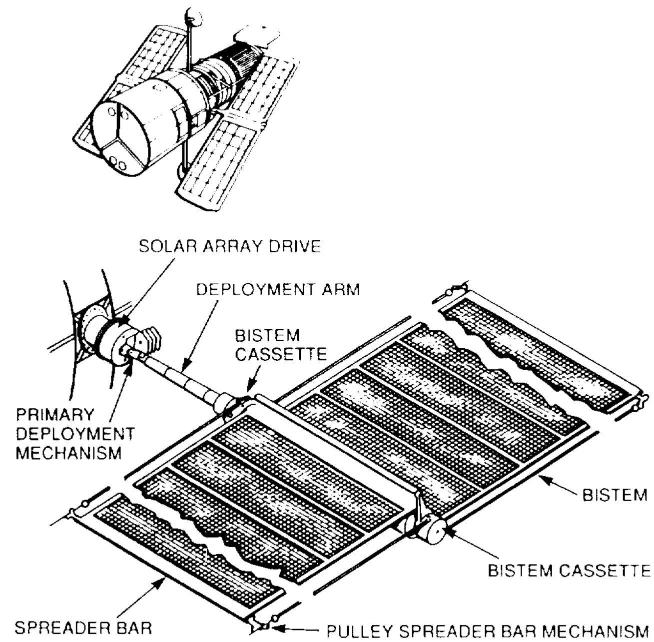


Figure 2-33 Solar Array Wing Detail

The primary deployment mechanism raises the solar array mast from the side of the SSM to a standing position perpendicular to the telescope. There are two mechanisms, one for each wing. Each mechanism has motors to raise the mast and supports to hold the mast in place when erect.

An astronaut can raise the array mast manually, if the drive power fails. Using a wrench fitting on the deployment drive, the astronaut hand-cranks the mast after releasing the latches.

Once the solar array is raised, the secondary deployment mechanism unfurls the wing blankets. Each wing has a secondary mechanism assembly: the cassette drum to hold solar panels, a cushion to protect the blanket, and motors and subassemblies. The assembly rolls out the blanket, applies tension evenly so the blankets stretch, and transfers data and power along the wing assembly. The blanket can roll out completely or part way. The secondary deployment mechanism also has a manual override (see Figure 2-34).

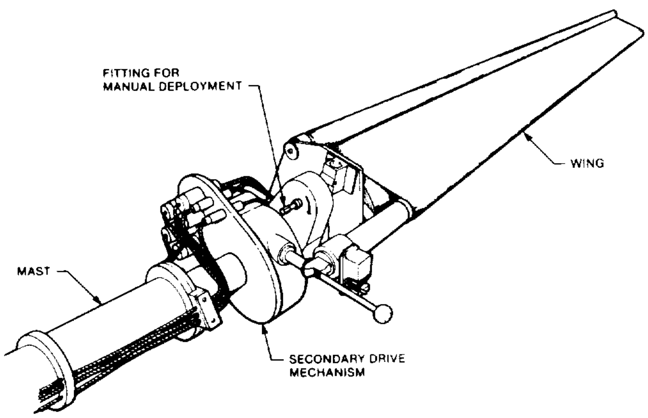


Figure 2-34 Fitting for Solar Array Manual Deployment

The solar array drive rotates the deployed array toward the sun, turning in either direction. The drive is at the base of each solar-array mast. Each drive has a motor that rotates the mast on command, and a brake to keep the array in a fixed position if the HST moves around in orbit. The drive can move and lock the solar array into any possible position for maintenance.

Each drive has a clamp ring that acts as a release mechanism if opened. This allows a crew member to jettison the entire solar array if deemed necessary by the STOCC.

The electronic control assembly controls and monitors all solar array system functions. It controls the primary and secondary deployment mechanisms and the solar array drive.

2.4.3 Operation

When the Hubble Space Telescope is in the cargo bay of the Orbiter, the solar arrays are stowed against the SSM with the masts latched against the sides of the forward shell and light shield. In this position the arrays extend just 26 in. (65 cm) from the SSM surface (see Figure 2-35).

Once the Orbiter places the Space Telescope into orbital position, the STOCC extends and unfurls the solar arrays by ground command. When the panels are unfurled and facing the sun, they begin absorbing solar energy and passing it to the electrical power subsystem.

2.5 SCIENTIFIC INSTRUMENT CONTROL AND DATA HANDLING UNIT

The Scientific Instruments Control and Data Handling unit (SI C&DH) controls the scientific instruments. It:

- Watches all scientific instrument systems to keep them synchronized and working

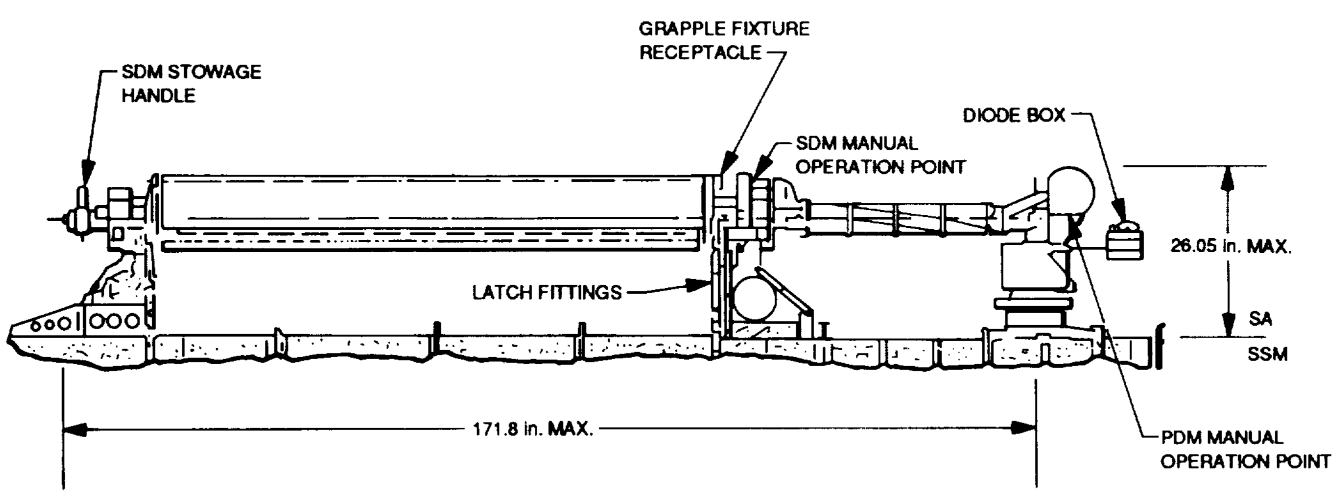


Figure 2-35 Solar Array Wing Stowed Against SSM

- Works with the data management unit to process, format, and communicate all science and engineering data created by the instruments

It was built by Fairchild Camera and Instrument Corp. and IBM.

2.5.1 SI C&DH Components

The SI C&DH is a collection of electronic components attached to an orbital replaceable unit tray and mounted on the door of bay 10 in the SSM equipment section. Small remote modules, also part of the SI C&DH system, are connected to each of the individual scientific instruments. The components that make up the SI C&DH are the NASA standard spacecraft computer, model I (NSSC-I); two STandard INTerface (STINT) circuit-board units for the computer; two control unit/science data formatter (CU/SCF) units; two central processor unit modules (CPMs); a power control unit (PCU); two remote interface units (RIU); and various memory, data and command communications lines (buses), connected by bus coupler units (BCU). The SI C&DH components are duplicated so the system can recover from any single failure. See Figure 2-36 for the layout of the SI C&DH components.

2.5.1.1 NASA Computer. The NASA standard spacecraft computer model I has a central processing unit module (CPM) and eight memory modules, each holding 8,192 18-bit words. One embedded software program (the "executive") runs the computer. It moves data, commands, and operation programs (called "applications") for individual scientific instruments in and out of the processing unit. The application programs monitor and control a specific instrument and analyze and manipulate the collected data.

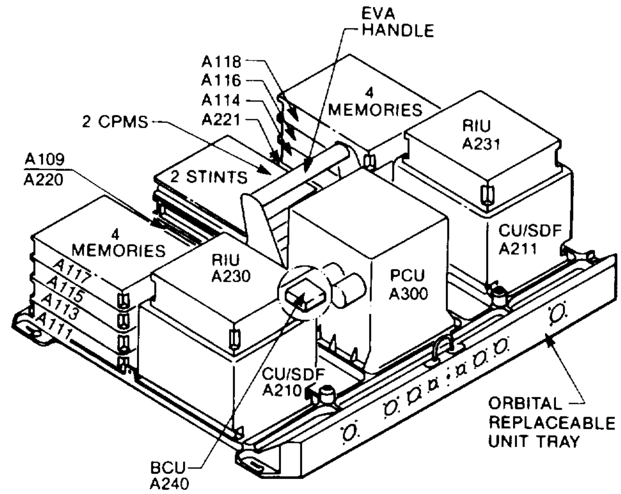


Figure 2-36 SI C&DH Components

The memory stores operational commands for execution when the HST is not in contact with the ground system. Each memory unit also has five areas reserved for commands and programs unique to each scientific instrument.

The computer can be reprogrammed from the ground for future requests or for working around failed equipment.

2.5.1.2 STINT Unit. The standard interface board is the communications bridge between the computer and the control unit/science data formatter.

2.5.1.3 Control Unit/Science Data Formatter. The heart of the SI C&DH is the control unit/science data formatter. It formats and sends to the right source all commands and data passing between the ground command, the data management unit, the NSSC-I computer, the SSM, and the scientific instruments. The unit has one microprocessor each for the control and formatting functions.

The control unit receives ground commands, data requests, science and engineering data, and system signals and information. Two examples of system signals are "time tags", clock signals that synchronize the entire spacecraft, and "processor interface tables" (PITs), or communications codes.

The unit transmits commands and requests after formatting them so the specific destination unit can read the signal. For example, ground commands and SSM commands are transmitted with different electronic signal formats. Ground commands use 27-bit words and SSM commands use 16-bit words. The formatter translates each command signal into a common format. The control unit also reformats and sends engineering and science data. Analysis of this data is an NSSC-I function.

2.5.1.4 Power Control Unit. The power control unit distributes and switches power among the components of the SI C&DH unit. It modulates the power as required by each unit. The computer memory boards, for example, variously need +5 volts (V), -5 V, and +12 V; the control unit, on the other hand, requires +28 V. The power control unit makes certain that voltage requirements are kept straight.

2.5.1.5 Remote Module Units. Remote module units transmit commands, clock and other system signals, and engineering data between the scientific instruments and the SI C&DH. The modules do not send science data. There are six remote modules in the Space Telescope: five attached to the scientific instruments, and one dedicated to the control and power units in the SI C&DH. Each module contains a remote interface unit and up to two expander units.

2.5.1.6 Communications Buses. The SI C&DH contains data bus lines that pass signals and data between the SI C&DH and the SIs. Each bus is multiplexed: one line sends system messages, commands, and engineering data requests to the module units, and a reply line transmits requested information and science data back to the SI C&DH. A bus coupler unit attaches the bus to each remote module. This isolates the module if the remote interface unit should fail. The SI C&DH coupler unit is on the orbital replaceable unit tray.

2.5.2 Operation

The SI C&DH handles scientific instrument system monitoring (timing, system checks, etc.), command processing, and data processing.

2.5.2.1 System Monitoring. Engineering data tells the monitoring computer whether instrument systems are functioning. At regular intervals, varying from every 500 msec to every 40 sec, the SI C&DH scans all monitoring devices for engineering data and passes it to the NSSC-I or to the SSM computer. The computers process or store the information. Any failure indicated by these constant tests could provoke a "safing hold" situation (see section 2.1.7, above).

2.5.2.2 Command Processing. Figure 2-37 illustrates the flow of commands within the SI C&DH. Commands enter the SI C&DH control unit/science data formatter (bottom right in the drawing) through the command data interface (ground commands) or the data interface unit (SSM commands). The control unit checks and reformats the commands which then go either to the remote modules or to the NSSC-I for storage. "Time-tagged" commands stored in the computer's memory (top right of drawing) also follow this process.

Each command is interpreted as "real time", as if the SI C&DH just received it. Many commands actually are stored commands activated by certain situations. For example, when the HST is positioned for a programmed observation using the Faint Object Spectrograph, that program is activated. The SI C&DH activates systems to perform whatever actions are required by a command, such as the pointing system to maneuver the HST.

2.5.2.3 Science Data Processing. Science data can come in from all scientific instruments at

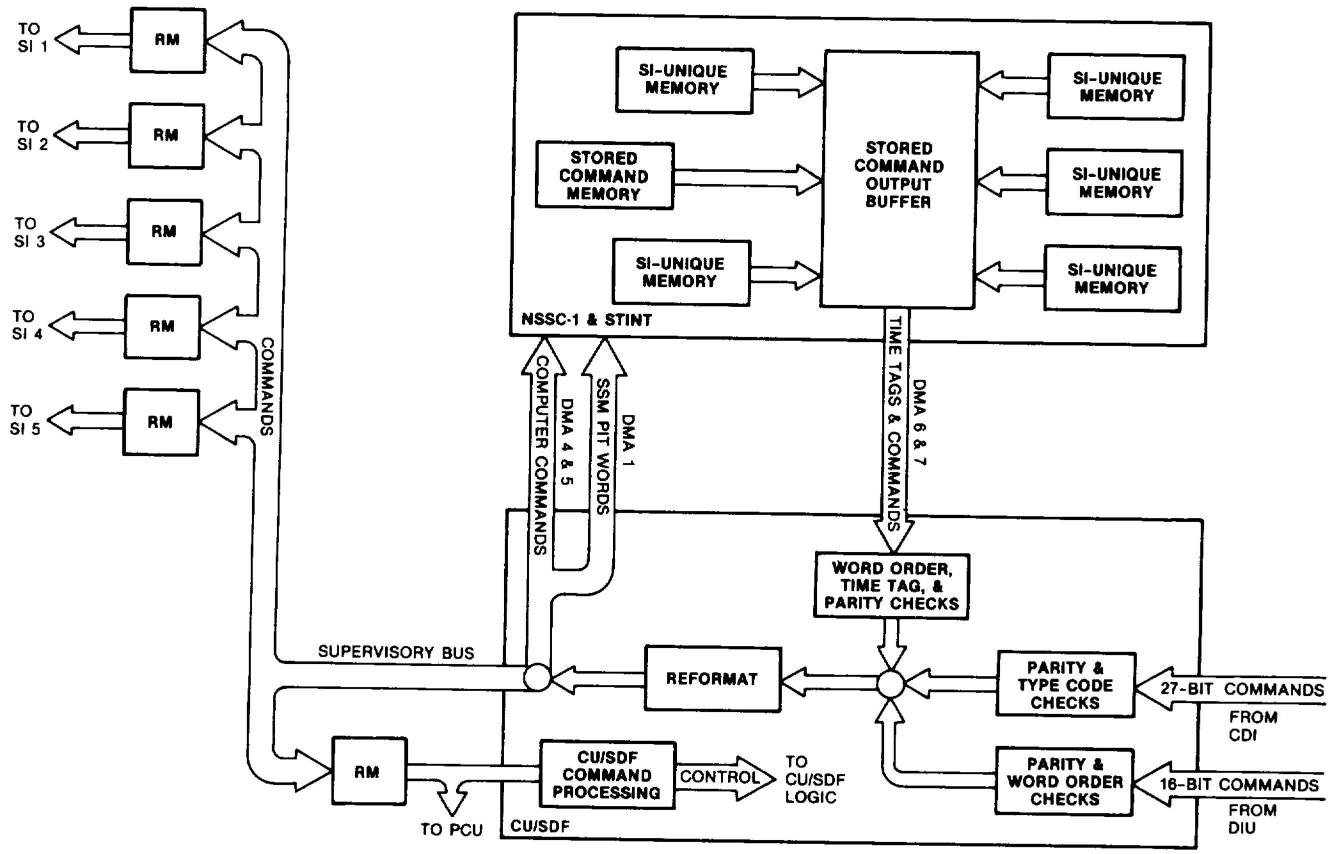


Figure 2-37 Command Flow, SI C&DH

once. The control unit transfers incoming science data through computer memory locations called packet buffers. It fills each buffer in order, switching between them as the buffers fill and empty. Each packet of data goes from the buffer to the NSSC-I for further processing, or directly to the SSM for storage or transmission to the ground. Data returns to the control unit after the computer processes it. When transmitting, the control unit must send a continuous stream of data, either full packet buffers or empty buffers called filler packets, to maintain a synchronized link with the SSM. Special checking codes (Reed-Solomon and pseudo-random noise) can be added to the data as options. See Figure 2-38 for the flow of science data in the HST.

2.6 SPACE SUPPORT EQUIPMENT

One of the unique features of the Hubble Space Telescope is that it can be maintained or repaired while in orbit, which will extend its mission-life considerably. The Space Shuttle will capture and stand the HST in the Orbiter cargo bay, and the Orbiter crew will perform any maintenance tasks required. Maintenance will require, at some time, replacing or exchanging scientific instruments and other major HST components. Major space support

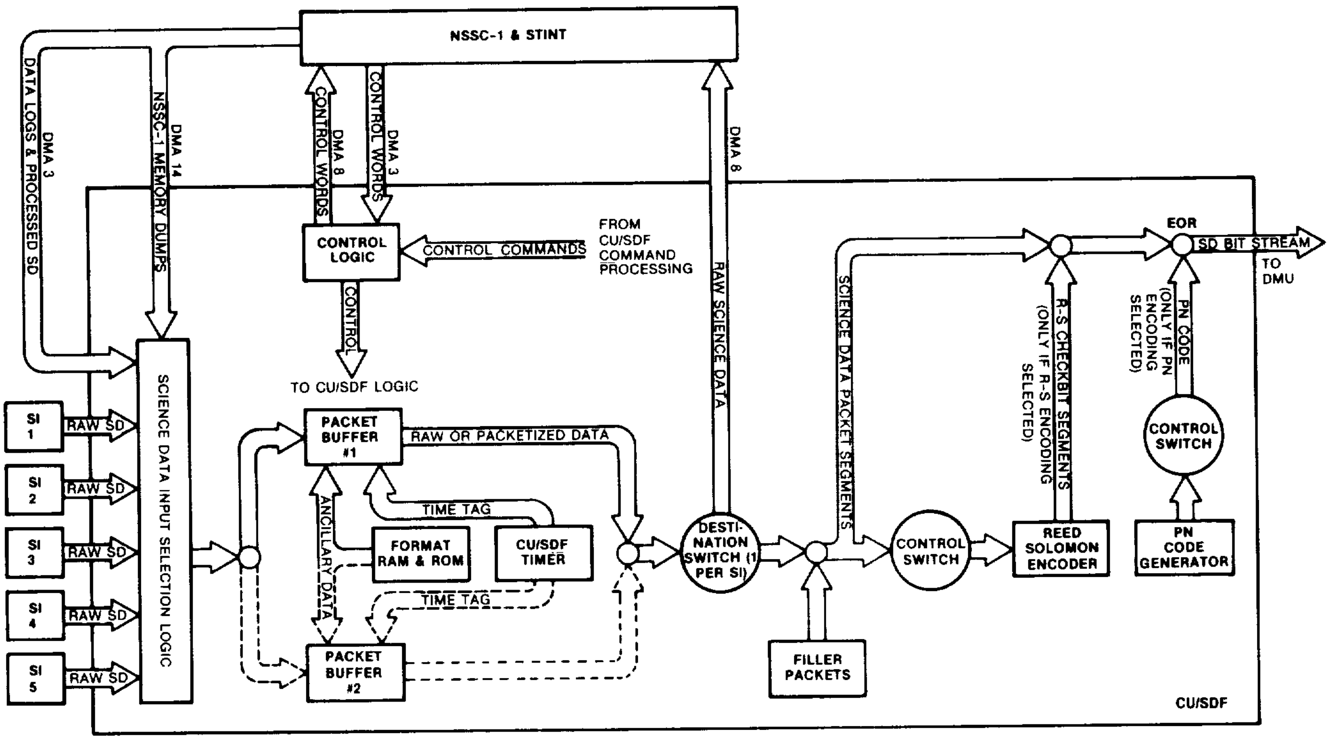


Figure 2-38 Flow of Science Data in the HST

equipment used during maintenance are the Flight Support Structure (FSS), the orbital replaceable units (ORU), the ORU carrier, and crew tools.

2.6.1 Flight Support Structure

The FSS is a platform that holds the berthed Space Telescope in place and rotates or tilts it during the servicing operation. The FSS superstructure has three major components: the outside horseshoe-shaped cradle with a supporting latch beam, a pivot arm, and the rotating FSS platform itself, on which the HST sits (see Figure 2-39).

The cradle is a two-thirds oval with supporting beams to strengthen the FSS. The FSS is placed in the bay of the Orbiter perpendicular to the Orbiter and held in place by latches. The latch beam spans and supports the cradle and is used to mount flight equipment.

The pivot arm, at the end of the cradle, supports and maneuvers the rotation platform to move the HST into intermediate positions up to 140 degrees toward the Orbiter cargo bay.

The rotation platform, between the ends of the cradle, holds the berthed spacecraft. The platform has a small television camera embedded in its base to guide the HST into the correct position on the platform. The rotation platform can rotate the telescope 360° once it is latched in place. The platform contains two umbilical units that carry power to the HST and support equipment during maintenance procedures.

2.6.2 Orbital Replaceable Unit Carrier

The orbital replaceable unit carrier (ORUC) is a Spacelab pallet filled with shelves and containers to hold orbital replaceable units (ORUs) for replacement or to be returned. The main components are the pallet, cradle, shelves, support structures, and latches to hold the

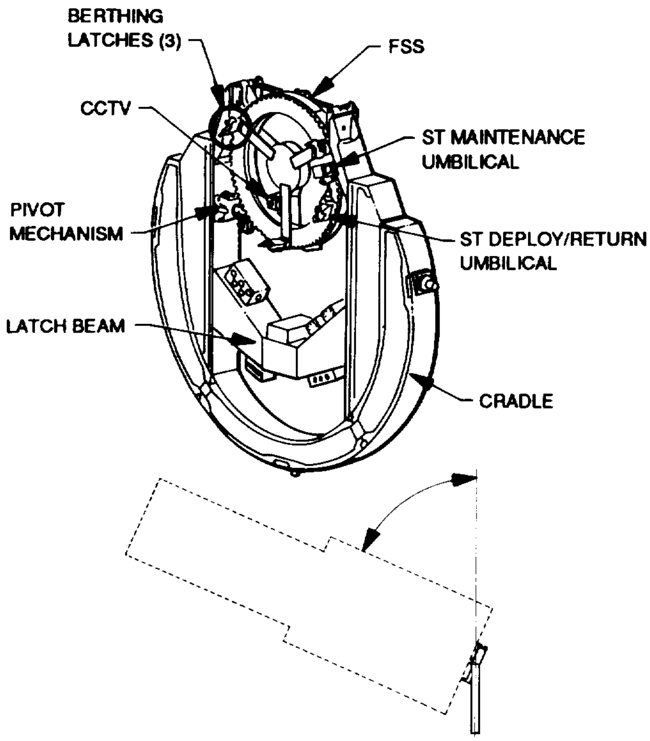


Figure 2–39 FSS Superstructure

equipment within the carrier. The carrier also has closed-door compartments, tethers, and crew aids that can be used by the crew during maintenance (see Figure 2-40).

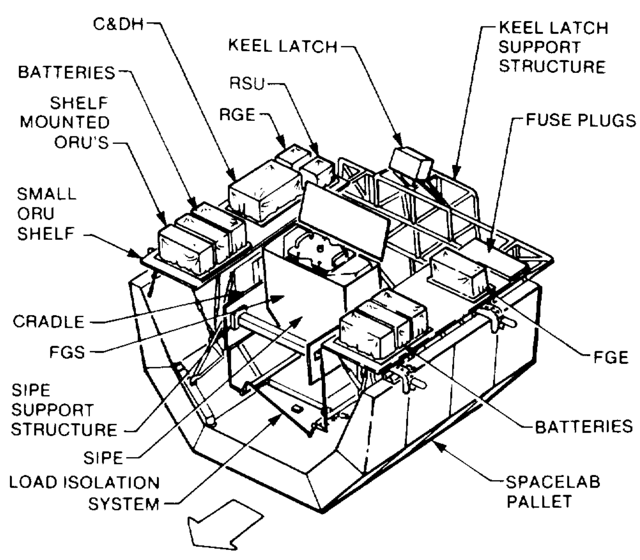


Figure 2–40 Typical ORU Configuration

2.6.3 Orbital Replaceable Units

Space Telescope designers selected modular HST components as Orbital Replaceable Units, which were critical subsystems throughout the HST that designers determined, through reliability analysis, might degrade during the HST's mission lifetime. Because these components might need replacing, they were designed as units — usually a self-contained box with simple fasteners and connectors — that could be replaced easily in one piece. A list of the replaceable units is in Appendix E.

There are 70 ORUs, comprising some 26 different components — some duplicated — ranging from the small fuse plugs to the telephone-booth-sized Faint Object Camera. The ORUs are arranged into a series of configuration options for the ORU carrier, and servicing requirements at the time will determine which ORU option — and which units in that option — will be included on a maintenance mission. A likely first candidate will be the HST batteries, which have a short lifespan. Four typical ORU configurations are shown in Figure 2-41.

2.6.4 Crew Aids

The Orbiter astronauts will perform extravehicular activity using many tools to help them replace instruments and equipment, move around the Space Telescope and the Orbiter bay, and operate manual override drives. Tools and equipment bolts, connectors, and other hardware were standardized not only for the HST but between the HST and the Space Shuttle, the Space Station, and the Orbital Maneuvering Vehicle. For example, grappling receptacles share common features to promote uniformity.

To get around the HST, the crew will use 225 feet of handrails that encircle the spacecraft. For visibility the rails are painted yellow. In addition, the crew can hold onto guide rails, the trunnion bars, and scuff plates that are fore and aft.

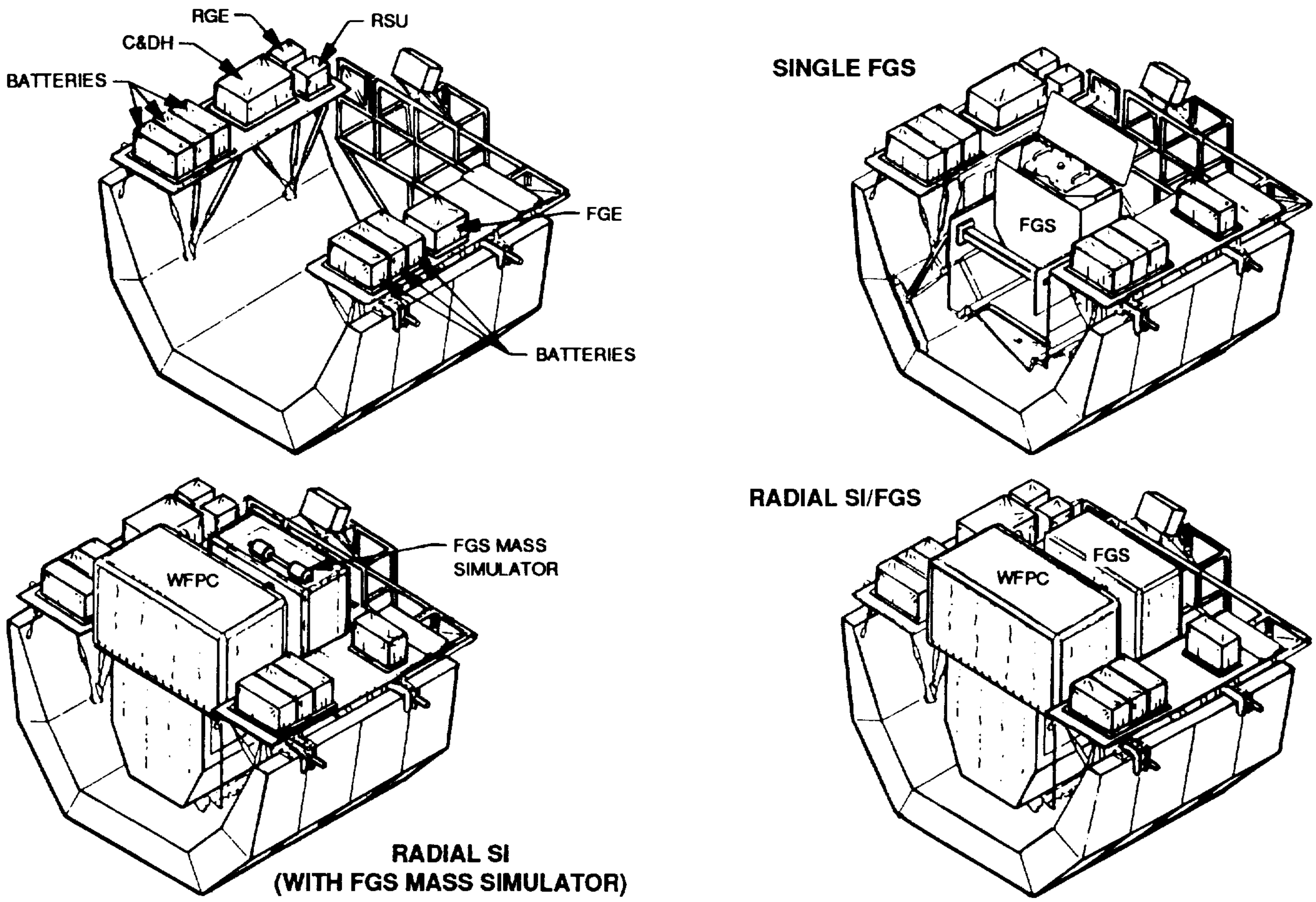


Figure 2–41 Four ORU Payloads

There are also portable handhold plates that the astronauts can install where there are not permanent handholds, such as on the fine guidance sensors.

Another tool is the portable foot restraint. Its use is depicted in Chapter 4, in section 4.3 on HST maintenance procedures. See Figure 2-42 for an illustration.

While the astronauts are working they will use tethers to hook tools to the EVA suits and tie replacement units to the HST. Each crew member will have a ratchet wrench to manually crank the antenna and array masts, should power fail for the mast drives. A power wrench also is available if hand-cranking is too time-consuming. Other hand tools include portable lights and a jettison handle, which attaches to sockets on the aperture door and solar array wings so the crew can push the equipment away from the HST.

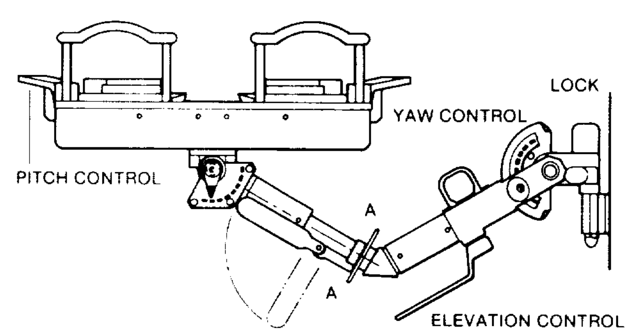


Figure 2–42 Portable Foot Restraint

Section 3
THE SCIENTIFIC INSTRUMENTS

The scientific instruments placed in the Hubble Space Telescope are the Faint Object Camera (FOC), the Faint Object Spectrograph (FOS), the Goddard High Resolution Spectrograph (GHRS), the High Speed Photometer (HSP), and the Wide Field/Planetary Camera (WF/PC). In addition, the fine guidance sensors (FGS) have a scientific role as astrometric instruments.

Four of the scientific instruments — the FOC, FOS, GHRS, and HSP — are located parallel to the telescope's optical axis so that the incoming images will fall into their entrance apertures. These instruments share the same dimensions so they can fit into the focal plane structure interchangeably.

The WF/PC and the three fine guidance sensors are placed just forward of the focal plane structure, at right angle to the optical axis. These four radial instruments rely on pick-off mirrors positioned in the optical path to deflect part of the incoming light into their respective entrances.

No scientific instrument receives all of the light in the focal plane, because of the small size of the instrument aperture or because the pick-off mirrors pick up only part of the beam. But each instrument can make calculations to adjust the Space Telescope position so the incoming light falls directly onto the specified instrument optics and detection system. This is called target acquisition.

The observing astronomy team can select different filters, gratings, or prisms — or even entirely separate optical systems — within one instrument to break the light into a spectrum. The filters, gratings, and other mechanical devices for the GHRS are operated by software embedded in the Scientific Instrument Control & Data Handling (SI C&DH) unit's computer. Other instruments have their own small computers that operate instrument mechanics and monitor and process the collection of data.

The operation process consists of:

- Selecting guide stars and locking onto them using the FGSs.
- Using a large aperture in the selected instrument to acquire the target.
- Selecting and positioning the appropriate filters and other devices needed to modify the incoming light.
- Exposing the instrument's detector to the light as long as needed to make the desired measurement.
- Processing the collected information for transmission to earth.
- Analyzing the data and using the information for further observations.

Physical descriptions of each scientific instrument, and possible astronomical targets, make up the rest of this chapter. The astrometric function of the fine guidance sensors is included.

3.1 THE FAINT OBJECT CAMERA

The FOC, more than the other instruments, will use the optical resolution of the HST to record objects in deep space more clearly than ever before. The FOC will be able to capture celestial lights with a magnitude to $28m_v$, which is so faint that ground-based observatories are not able to detect the light from those images. The FOC will study the evolution of star formation, examine galaxies and faint objects like quasars, and possibly locate planets existing outside our Solar System.

3.1.1 Physical Description

The FOC was designed by the European Space Agency (ESA) and built by Dornier System in West Germany and British Aerospace in England. Its physical dimensions are 3 x 3 x 7 ft (0.9 x 0.9 x 2.2 m), roughly the size of a telephone booth; it weighs about 700 lb (318 kg). It has four major subsystems. The loadcarrying structure assembly houses the optical elements and the photon-detector head elements. The optomechanical assembly contains an optical bench that supports the main optical and mechanical equipment. The electronic bay assembly holds the data-processing and data-handling equipment and system control. The photon-detector assembly is composed of the photon-detection system, data-processing electronics, and power supply for the detectors.

The major subsystems are pictured in Figure 3-1.

After the HST is positioned correctly, light from an object is focused on the FOC aperture. The light, which consists of many energy photons, is channeled down one of two optical pathways. At the end of the pathway each photon enters the FOC detection device and is detected. The recorded image is placed in a science data store and can be intensified by a longer exposure. The data is transmitted to earth, where it can be enhanced by computer graphics into an image of the celestial object.

3.1.1.1 Optical System. The optical system of the FOC consists of two independent systems, using two different apertures and focal ratios, f/96 and f/48. These are similar to the f-stops on earth cameras except for the larger ratios. Both optics systems operate in the same way: the incoming light travels through the selected FOC aperture and into a small Cassegrain telescope that is like the main telescope. The light is reflected from a primary concave mirror to a secondary convex mirror on a different plane, then onto a folding mirror, and finally onto the detector tube for enhancing and processing. Both optical pathways contain filter wheels used to isolate critical wavelength beams for specific studies. See Figure 3-2 for the optical layout.

The folding mirrors increase the focal length without increasing the FOC's physical length, move to adjust the focus, and correct for astigmatism in the HST telescope mechanism.

Each optic system aperture has a shutter that remains closed, completely blocking out light until the FOC is needed for astronomical observations. When the shutter is closed, a mirror on it can reflect a beam of light coming from a calibration source down the optic path to measure the light-detecting capability of the detectors. The FOC response to visible light and geometric light distortions produced by the FOC can also be determined.

In both optical systems there is a zoom option that doubles the field of view light while maintaining the same spectral resolution.

The f/96 Optics System. This system produces the Space Telescope's best angular resolution. It increases the HST focal ratio of f/24 four-fold, and a special device inserted in the path can increase that ratio up to f/288. There is a tradeoff, however, because the f/96 optical system has a narrow field of view, at best (22 arcsec)^2, but it allows the FOC to distinguish between two objects only 0.01 arcsec apart. This is a crucial requirement for studying stars within a distant globular cluster, which appear so close together that ground instruments cannot distinguish between them.

The f/96 optics have two special features to block unwanted light from the field of view: two coronographic fingers in the aperture, and an

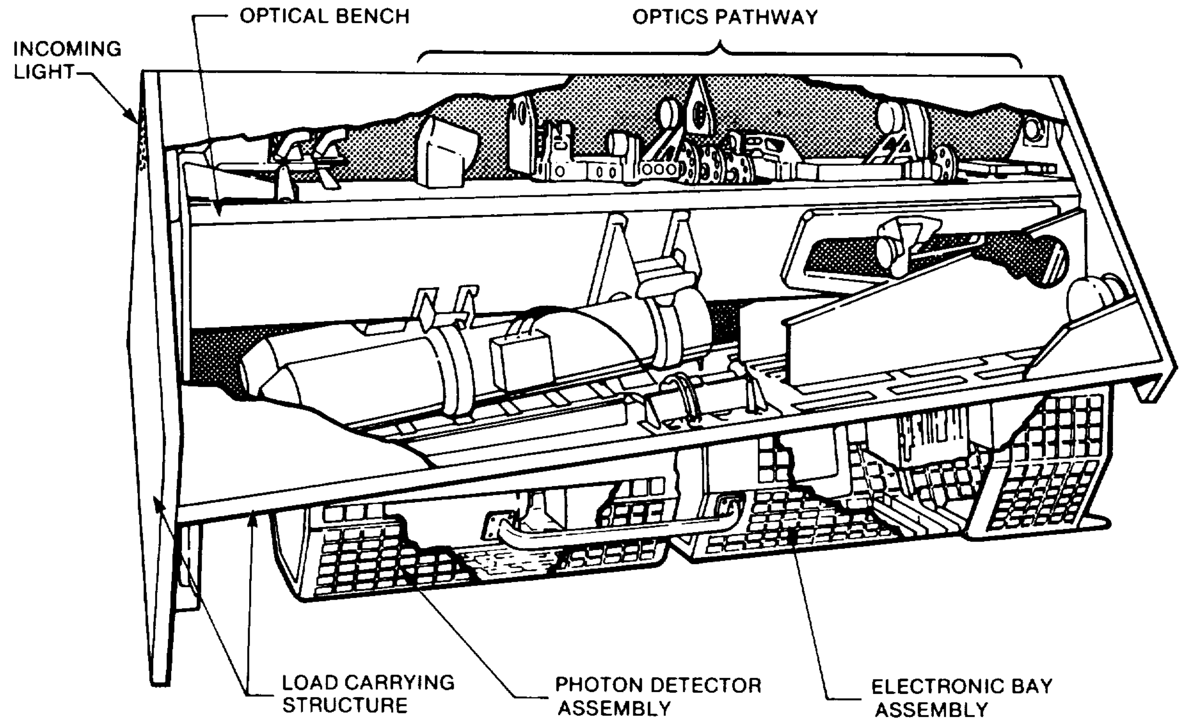


Figure 3–1 FOC Major Subsystems

apodizer mask which can be moved into the f/96 optical path.

The fingers can block bright objects that are near the target of the FOC, so the targeted object can be detected with less intrusive light. This is useful when observing a bright star that has a faint companion suspected of being a planet.

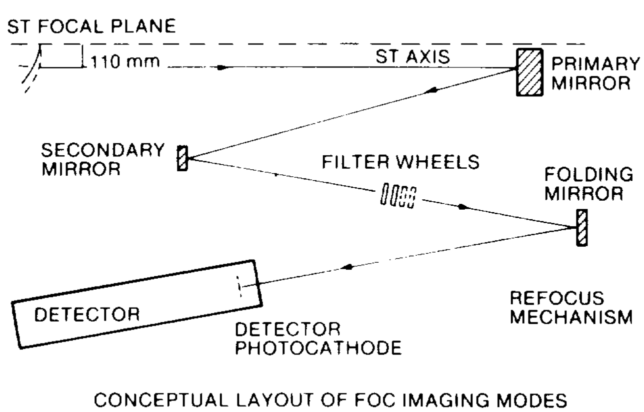


Figure 3–2 Layout, FOC Optical Relay Systems

The high-resolution apodizer is embedded within another miniature Cassegrain telescope. It is near the edge of the f/96 FOV but includes the smaller coronographic finger. The apodizer is a masking device that blocks out stray light reflected off the secondary mirror and ST optical support structures. The Cassegrain system increases the focal ratio to f/288. This narrows the field of view even further, but increases the resolution needed to detect faint objects obscured by brighter ones. The FOC can detect an object almost 17 magnitudes fainter than its bright companion only one arcsec away. This is like being able to see a dim star in full moonlight.

Another feature in the f/96 optical path is a series of four filter wheels, which contain 48 filters, prisms, and other optical devices. For example, if the astronomers choose, they can send the beam through a magnesium-fluoride prism to emphasize the far ultraviolet end of the spectrum. See Figure 3-3 for the complete f/96 optical layout.

The f/48 Optics System. This system will allow a wider field of view at (44 arcsec)^2, but the resolution will be less than with the f/96 optics system. The f/48 system thus will be reserved for spectrographic purposes, other duties such as target searches, and as a secondary optics relay. To use the f/48 system the HST orbital position may need to be readjusted to redirect the main light path into the f/48 aperture. The f/48 optics system is identical in overall structure to the f/96 and shares the same calibration device. The separate components of the f/48 system are the reflecting optics, two filter wheels, and a detector like the f/96 detector.

The f/48 system also has a 20-arcsec-long spectroscopic slit in its aperture. A special mirror rotated into the optical path diverts the light coming through the slit onto a diffraction grating. This grating breaks the light into a spectrum of the composite wavelengths. The dispersed light reflects into the detector.

The spectrographic slit has a limited spectral range, depending upon the spectral order chosen. It ranges from 3600 to 5400 Å for the first order to 1200 to 1800 Å for the fourth order. The spectral resolution of the diffracted light is 2000, which means the detectors register spectral lines only one angstrom apart in the 2000-Å range. This spectral resolution quality falls between the Faint Object Spectrograph and High Resolution Spectrograph. The FOC spectrograph's value is in measuring light sources that spread across many light years, such as a galaxy or nebula.

The f/48 optics also include two filter wheels, which can be used either with the main optics or with the spectrographic optics for specialized viewing. The filters can, for example, block out

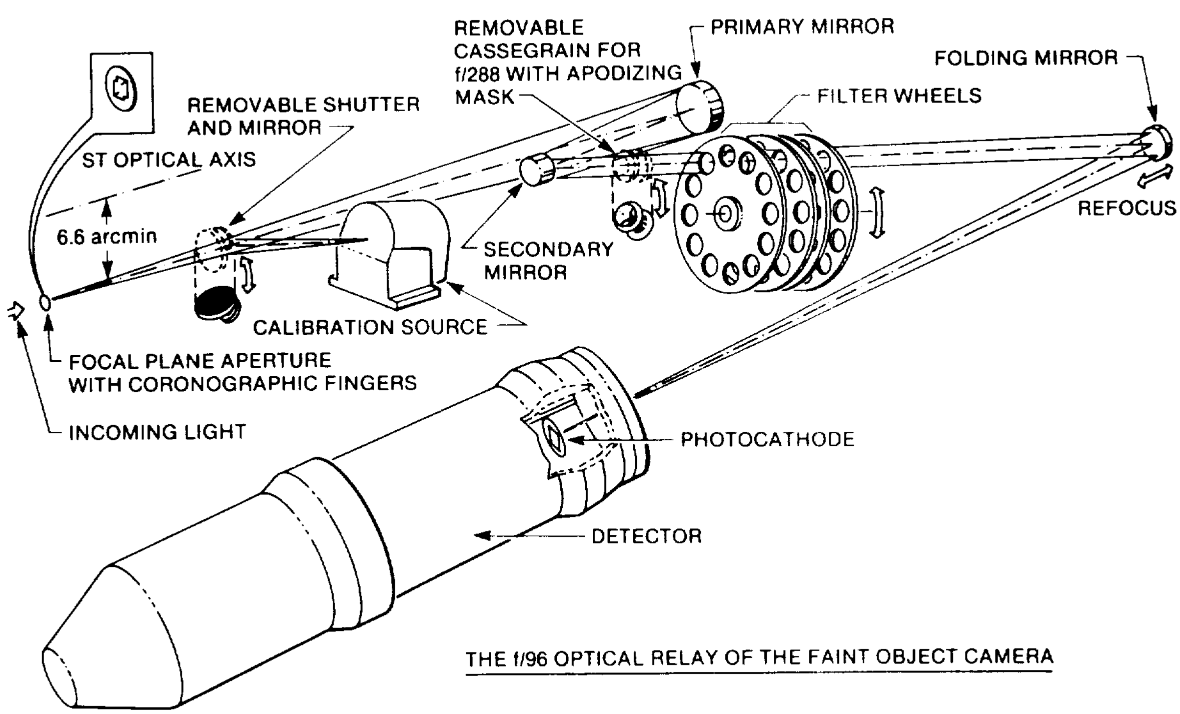


Figure 3–3 F/96 Optical Relay System Layout

certain wavelengths or select very specific wavelength ranges. Figure 3-4 is the detailed f/48 optics layout.

3.1.2.2 **The Photon Detector System.** There are two identical detectors in the FOC. They are sensitive to radiation between 1150 and 6500 Å. The photons from the target source enter an image intensifier, where the photons are converted to electrons. High voltage accelerates the electrons in three steps. Then the detector reconverts the electron output to photons, providing 100,000 photons for every original electron. An intensified image is produced by a high-sensitivity television-type camera tube, which sends an amplified video signal to the FOC video processing unit. Figure 3-5 illustrates the path of a photon from the point when it hits the detector to its processing.

The center location of each photon burst is determined by the video processing unit and stored in the science data store. Typically a photon burst is a spot roughly 75 to 100 microns in diameter. Every time an incoming photon bursts onto the diodes at the same location, the recorded light is intensified at that position. An light can be produced in a period between ten minutes and ten hours, depending upon the brightness of the object being observed. The science data store will count or record up to 65,535 photon bursts at each location, depending upon the length of the observation. For extremely distant objects with magnitudes to 28, the exposure time may last up to ten hours.

The size of the completed picture depends upon the light size originally selected. The standard light format is a square measuring 512 by 512 pixels, with each pixel 25 by 25 micrometers (1/10,000th of an inch) in size. Other formats can be chosen for larger, smaller, or differently-shaped lights, and the pixel size can be doubled. This will affect the number of photons

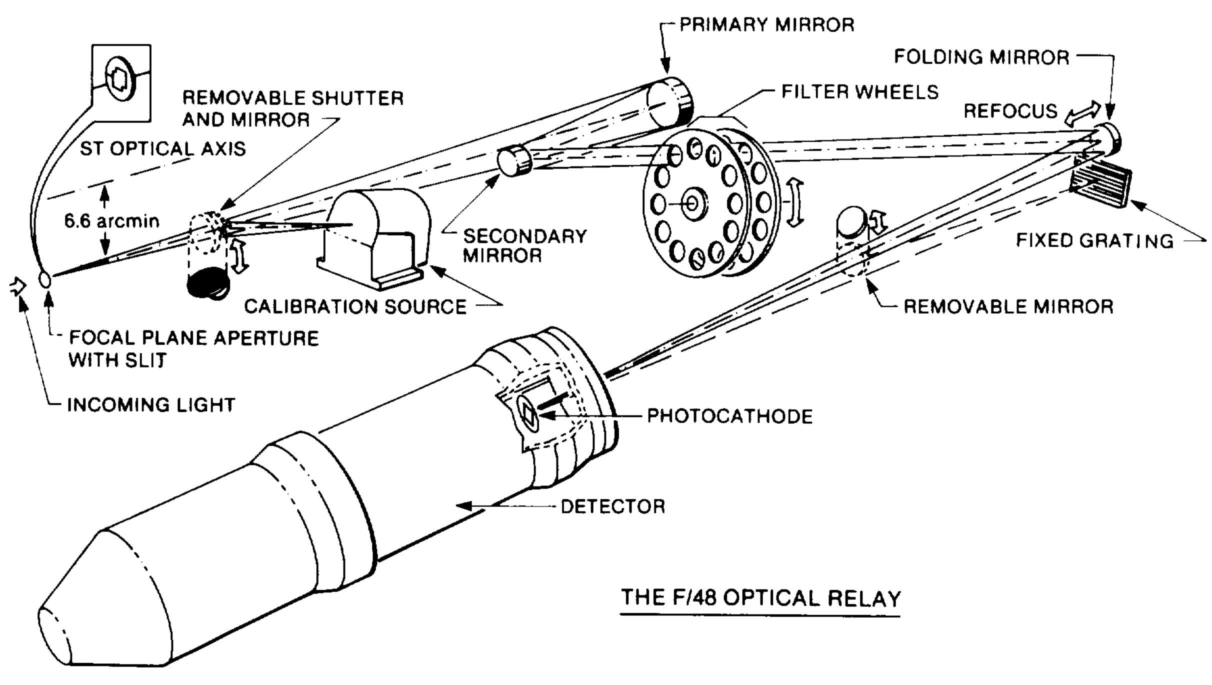


Figure 3–4 F/48 Optics Relay System Layout

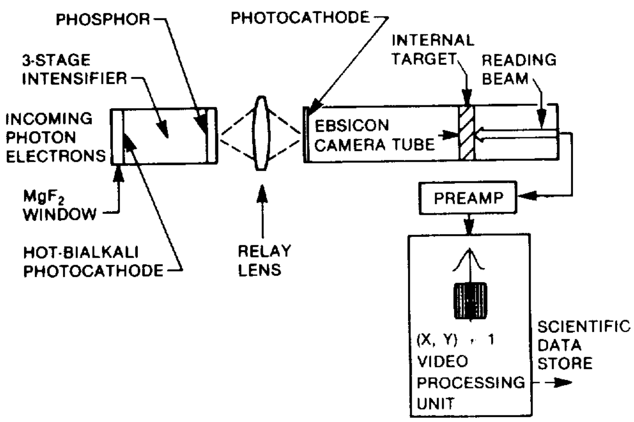


Figure 3–5 Photon Detection System

the FOC can count because of data storage and transmission limits.

One advantage of the detector system is that the light in the science data store can be viewed at any time without destroying the data being collected. This is quite useful for intermediate study of the developing light.

The light is stored on magnetic tape by the HST tape recorders until it can be sent to the Space Telescope Operations Control Center (STOCC) via the Tracking and Data Relay Satellite System (TDRSS).

3.1.1.3 FOC Electronics. The final step in the FOC process is electronic support, which includes physical support, dataprocessing, and transmission and is performed by the FOC electronics system. The system also services electronic functions, such as the thermal control to keep the FOC electronics and optics protected in space.

There are command and communications units linking the FOC to the Space Telescope, particularly to the NASA standard spacecraft computer (NSSC-I), the Scientific Instrument Control & Data Handling unit computer which, with the FOC's on-board computer as a backup, operates the FOC.

3.1.2 Observation Modes

The Faint Object Camera has four observation modes: targeting, imaging, occultation, and spectrographic.

Targeting mode precedes any observations using the FOC's coronographic or spectrographic devices. A special exposure of the target, using the FOC, is processed by the SI C&DH to find the target within the FOC field of view. Then the HST is repointed to place the light onto the coronographic finger or spectrographic slit, located on the edge of the FOC field of view.

Imaging mode uses either of the optics system to take a direct image of a target. Various formats and filters are selected to change the image size and/or the wavelength range.

Occultation is the eclipsing of one celestial body by another object. Occultation mode uses the coronographic fingers and the high-resolution apodizer to occult a bright object so astronomers can study the surrounding background. An example would be occulting a quasar to see if it exists within a galaxy visually obscured by the quasar's brightness.

Spectrographic mode uses the long slit in the f/48 aperture to diffract the incoming light into composite wavelengths. Filters and a cross-dispersing prism will allow astronomers to separate the light into narrow wavelength ranges for specific study.

3.1.3 Faint Object Camera Specifications

Table 3-1 Faint Object Camera Specifications

FAINT-OBJECT CAMERA	
Weight	700 lb (318 kg)
Dimensions	3x3x7 ft (0.9x0.9x2.2 m)
Principal Investigator	F.D. Macchetto, Eur. Space Agny
Contractor	ESA (Dornier, Matra Corp.)
Optical Modes	f/96 f/48
Field of View	11.2, 22 arcsec^2
Magnitude Range	5-28 m_v
Wavelength Range	1150-6500 Ang.

SPECIFICATION NOTES:

- Focal ratio can be adjusted as commanded from the ground. The most frequent use will be f/96.
- The light will be resolved clearly except for slight light halos imposed by the optical limitations of the Space Telescope itself.
- Fields of view listed are the maximum for each focal ratio.
- The wavelengths studied usually will be a band within the maximum range. For example, one study may concentrate on the band from 1200 to 1800 Angstroms.
- Specific signal-to-noise (clear light to interference) ratios depend upon observation ranges and exposure times but indicate the FOC's limits.

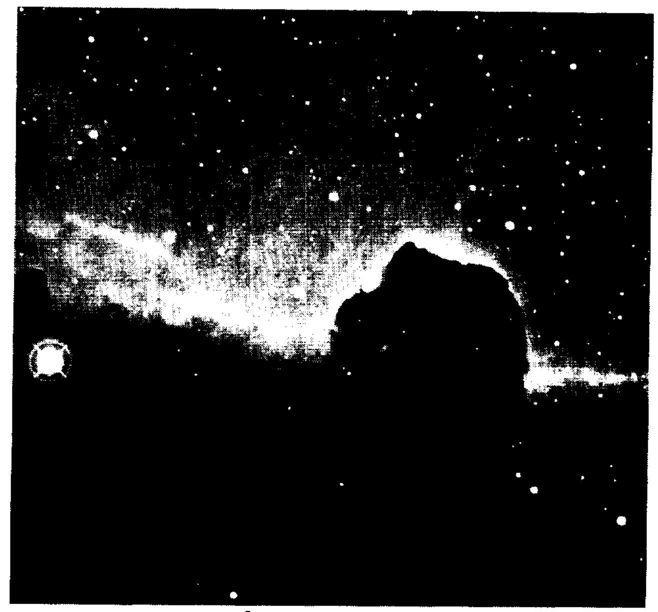
3.1.4 Observations

The Faint Object Camera will be used, by itself and in conjunction with other HST scientific instruments, on a number of important observations. Among its priorities are:

- Studying interstellar gas clouds for evidence relating to the formation and evolution of stars
- Measuring the distance of the farthest galaxies and quasars
- Examining globular clusters and normal and irregular galaxies
- Providing high resolution observations of various Solar System phenomena

These possible explorations are discussed below.

3.1.4.1 Stellar Evolution. Astronomers speculate that stars form out of the gas and microscopic dust referred to as interstellar matter and visible as huge clouds in the heavens. A good example of these clouds is the dark-cloud pattern in the Horsehead Nebula. See Figure 3-6.



Courtesy National Optical Astronomy Observatories.

Figure 3-6 The Horsehead Nebula, A Dark Gas Cloud

Stellar formation, scientists believe, begins when the gas clouds are buffeted by shock waves coming from nearby newly-formed and internally-combusting stars, from supernova explosions, and from the whirling movement of the arms of spiral galaxies. This violent motion collapses the gas clouds onto themselves. Growing hotter and heavier, the clouds increasingly compress into a spiraling mass of matter around a dense core. Eventually the mass ignites in a nuclear explosion and become a protostar.

Unfortunately, clear observations of a protostar in development is difficult because of the surrounding mass of matter, often called a "cocoon." When a new star begins igniting, the explosions blow away much of the obscuring gas, leaving only scattered clumps of condensing gaseous objects orbiting the star. These clumps, astronomers theorize, could eventually develop into planets.

The FOC team hopes to observe as much of this process as possible, from cloud fragmentation to, perhaps, a clear view of a protostar with preplanetary matter. Studying candidate protostars and dark clouds over months, using the camera and its spectrographic equipment, the FOC may capture dynamic changes. Figure 3-7 is an artist's conception of a protostar with preplanetary matter circling it.

Certain stars hold special interest in the search for planets beyond our Solar System. Astronomers have observed variations in the motion of these single stars that suggest the existence of a companion object, perhaps a planet. Observations using the masking capabilities of the FOC will produce a muddy picture because of the background starlight. But, by taking images from different angles, the FOC might be able to isolate any faint companions. See Figure 3-8 for an artist's rendering of the photographic technique.

3.1.4.2 Measuring Distances. What is the extent of the universe? What is the distance between stars? The FOC, with its high angular resolution and ability to detect objects light years beyond previous observations, will help astronomers calculate direct geometric distances to astronomical objects. By examining motion and parallaxes for clusters of stars, along with the speed at which material is dispersed from the stars, astronomers can accurately measure distances.

Figure 3–7 Protostar with Preplanetary Matter

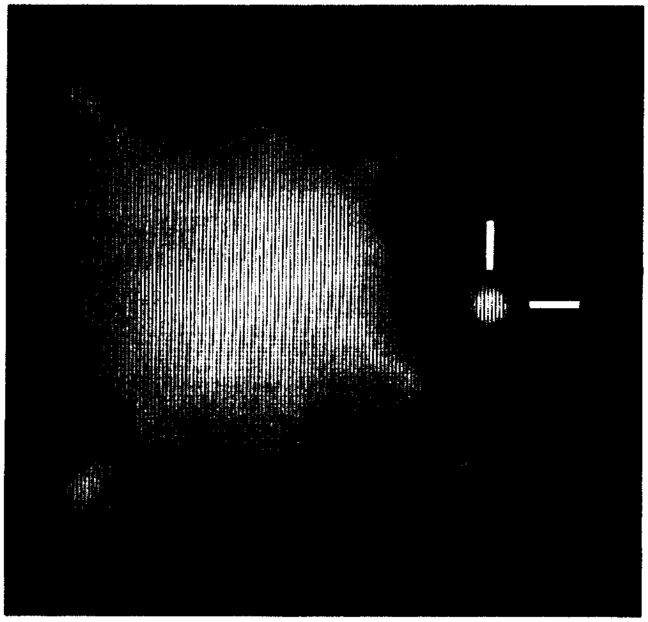
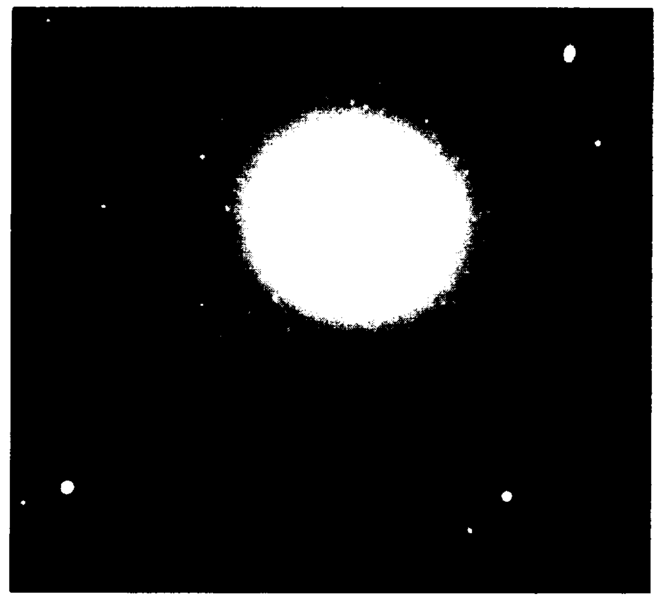


Figure 3–8 "Photographing" A Secondary Body

An important distance measurement indicator will be the Large Magellanic Cloud. The clouds contain standard distance indicators known as Cepheid variables, which radiate or pulse regularly at two distinct magnitudes. Astronomers can calculate relative distances from the relative magnitude of different Cepheids. Once astronomers measure the precise distance to the Cepheids in the Large Magellanic Cloud, they can measure Cepheids in more distant systems more accurately.

3.1.4.3 Globular Clusters and Galaxies. Clusters of stars, called globular clusters, and a variety of galaxy types fill the universe. Many questions arise when studying clusters and galaxies, and the FOC and other scientific instruments will be used to seek answers. One question concerns the centers of some clusters and galaxies, which radiate more energy than the surrounding galaxy itself. Are the bright centers filled with clumps of stars massed together? Is the center a massive object sized beyond comprehension? A high-resolution study of these central regions may reveal the source of that intense radiation.

Of particular interest is the center of elliptical galaxy NGC 4486, also known as Messier 87 (Figure 3-9). Scientists suspect there is a massive object at its center, created by stellar collisions and collapsed matter that add to the growing nucleus of the galaxy. If the center is a single object, it could be a quasar producing the tremendous energy radiating from the center (Figure 3-10).



Courtesy National Optical Astronomy Observatories.

Figure 3–9 The Elliptical Galaxy Messier 87

The observation program would examine the galaxy center using the f/96 optics system, with a broad-band filter, and the spectrographics of the f/48 optics.

The FOC also will concentrate on known quasars to see if there are surrounding galaxies hidden by the tremendous luminosity of the quasar. The masking ability of the FOC may help discover these faint galaxies. Since many quasars may have formed shortly after the Big Bang, they and their galaxies may reveal information about the early composition and development of the universe.

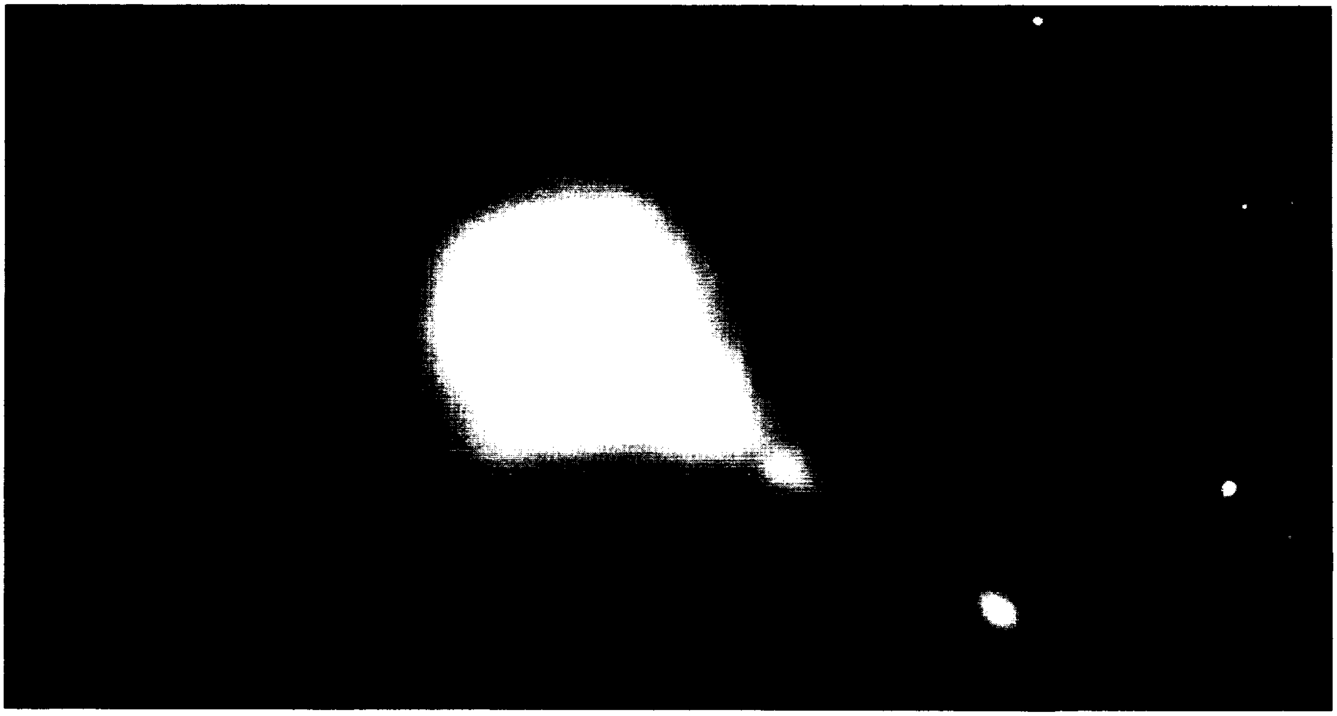


Figure 3–10 Quasar Hypothetically Centered In Messier 87

3.1.4.4 Examining Solar System Objects. With the FOC, astronomers can observe the planets, moons, asteroids, and other bodies in the Solar System more clearly than from ground-based observatories. Scientists will obtain data similar in detail to that obtained from the Voyager spacecraft. But the FOC will allow astronomers to examine a planetary object for years instead of the brief time dictated by Voyager's "fly-by" trajectories. Planetary observations, moreover, can take place even when the FOC cannot examine faint objects because of light interference from the sun, earth, or moon.

Direct observation of the surface of Mars, for example, will advance scientific understanding of Martian geography and weather, such as Mars wind patterns and dust storm velocities; white-cloud formation; and seasonal polar-cap movement. Closeups of Jupiter, Saturn, Neptune, Uranus, and Pluto will expand our knowledge of the surface composition and dynamics on these outer planets, and it is possible that the FOC may discover additional satellites of these planets. The FOC angular resolution will allow examination of the smaller asteroids and planetary moons in greater detail than ever before to determine accurate dimensions, axis orientation, orbits, and composition. The FOC also will study comets using its spectrographic optics, the coronographic device, and a variety of filters.

3.2 FAINT OBJECT SPECTROGRAPH

The Faint Object Spectrograph (FOS) and the Goddard High Resolution Spectrograph (GHRS) are companion instruments. The FOS studies light from very faint objects, while the GHRS studies brighter light in much greater detail. Each is most sensitive to different portions of the spectrum, but they overlap somewhat in mid-range to back up each other.

The FOS is a medium-resolution instrument. It captures faint objects detecting a broad spectral range. For objects with apparent magnitudes in the range 22 and 26m_V, the FOS has a spectral resolution of 250. This means that in the

1500-Angstrom range it can differentiate spectral lines as close as six Angstroms apart. For brighter objects the resolution increases to 1300, separating spectral lines as close as 1.2 Angstroms. In both cases, the FOS can display a spectral range from 1100 Å, in the ultraviolet, to 8000 Å, in the near infrared. This will produce very broad chemical portraits of targeted objects, because this spectral range includes the emissions of most of the chemical components of stars.

In addition to studying the chemical nature of faint objects, the FOS will help measure the velocity of celestial targets. The FOS also has spectrophotometric (wavelength and intensity of light) and spectropolarimetric (wavelength and polarization of light) capabilities. The former can help discover the interactions between hot, X-ray-emitting binary stars and their cooler stellar companions bombarded by the X-rays. Spectropolarimetric observations reveal information about the internal processes of interstellar dust clouds, which can polarize the light passing through them.

3.2.1 Physical Description

The FOS is rectangular, 3 x 3 x 7 ft (0.9 x 0.9 x 2.2 m) and 680 lb (309 kg), and parallel to the HST optical axis. Designed under the leadership of R. J. Harms, now Vice President of Applied Research Corp., the FOS was built by Martin Marietta Corp.

There are two optical paths in the instrument — one leads to a red-sensitive Digicon detector for sources emitting longer (red) wavelengths, and the other leads a blue-sensitive detector for objects emitting short (blue) wavelengths. The FOS components consist of the optics; electronics, power, and communication systems; and structural support for the optical and electronics equipment. See Figure 3-11.

3.2.1.1 Optical System. The FOS optical system contains special apertures, mirrors, a filter/grating wheel, and the separate detectors.

There is an entrance port leading to the aperture assembly. The aperture port remains closed until the FOS begins operating. Pointing the HST places the incoming light down one of two optical paths and into one of 12 apertures.

The largest aperture, 4.3 arcsec in diameter, is for target acquisition. The smaller apertures are used for various observations. Two occulting apertures capture faint light surrounding a bright target (e.g., a galaxy surrounding a quasar). Four apertures observe the target and sky background with different fields of view. One aperture serves for wide targets, such as galaxies, while one is blank to act as a light shield.

Three apertures are specialized for spectropolarimetry. These apertures send the light through a polarization analyzer. Light waves oscillate in a particular plane if they pass through a magnetic field, and the analyzer can rotate so only light polarized in a certain plane passes through. The planes are selected in increments of 22 degrees.

Light travels through the selected aperture onto a prismatic mirror, which reflects the beam 22 degrees away from the HST optical axis. The light goes through an order-blocking filter mounted on the filter/grating wheel. This filter passes light in the desired spectral range. For example, if that range is 4500 - 6800 Å, the filter blocks all light waves shorter than 4500 Å and longer than 6800 Å. The filtered light reflects off a collimating mirror, which sends the beam back to the grating wheel.

The filter/grating wheel is a carrousel which contains a variety of gratings. Six gratings cover the range 1150 to 9000 Å with moderate resolution of 1300. Two gratings provide low spectral resolution (250) for the ranges 1150 to

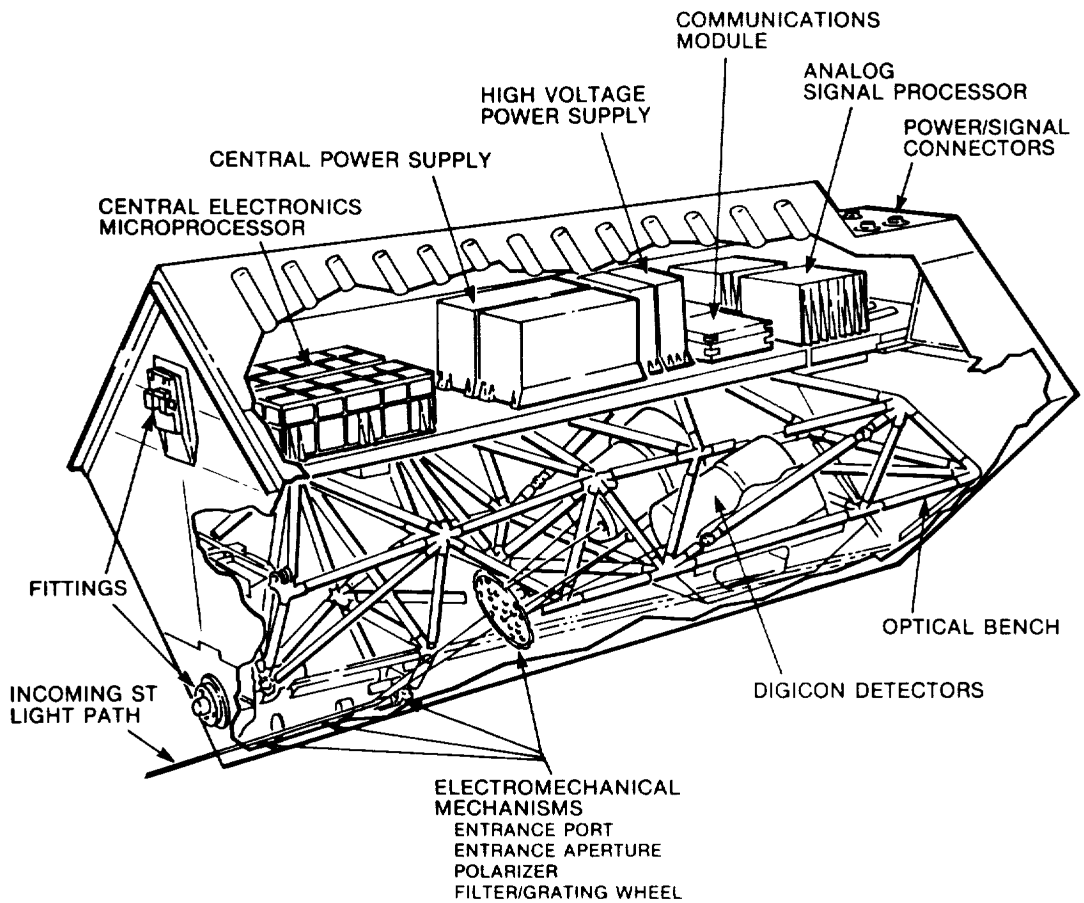


Figure 3-11 The FOS Components

2500 Å and 3500 to 7000 Å. A prism is available for long, visible wavelengths, but with limited spectral resolution of 100. A clear mirror passes an undispersed light for target aiming.

3.2.1.2 Digicon Detectors. From the grating wheel the light continues onto the Digicon that is sensitive to the selected wavelength spectrum. For the blue-sensitive detector, that range is 1100 to 5000 Å; for the red-sensitive detector, the range is from 1700 to 8000 Å. Only one Digicon can be used at a time.

Each FOS detector has a photocathode designed to release electrons only from a specific spectral range of photons. A magnetic field boosts and focuses the incoming electrons onto a string of silicon diodes. Each diode records and amplifies a "pulse" as each electron hits the diode. The diodes can record each pulse and pass it along immediately, or accumulate data, according to the observation instructions. The FOS will collect at least 99% of all pulses from a target over four hours on 99% of the operating diodes, with the system held steady. Figure 3-12 details the optical system path, from entrance port to detector.

3.2.1.3 Electronics, Power, Communications. The analog signal processor, central electronics assembly, power supply, and remote communications system are all above the optics bench support. The signal from the detector diodes goes to the analog processor for shaping into spectra, then it is sent to the central electronics assembly for final processing and transmission.

The central electronics assembly contains two microprocessors and support electronics, one for each detector. The small computers rotate the filter/grating wheel to the desired setting, based on preset STOCC commands, operate the magnetic focus system to direct electrons toward the diode array, and control the pulse-counting mechanism. Then the central electronics assembly sends data, through the communications unit, to the SI C&DH unit in the Support Systems Module.

In addition to science data, the FOS produces engineering data, such as temperatures, voltages, and processing data from the microprocessors. All data are stored on tape or sent directly to the ground.

3.2.2 Operational Modes

The FOS has four modes for collecting science data. They are spectroscopic, time-resolved, time-tagged/rapid readout, and spectropolarimetric modes.

The spectroscopic operation will be the standard way to collect data. The astronomer making the observation will select a grating for the desired wavelength range and spectral resolution required. The incoming light goes to the correct Digicon detector for a predetermined observation time, from several minutes to four hours. The resulting data are read out to the HST or ground communications link at regular intervals.

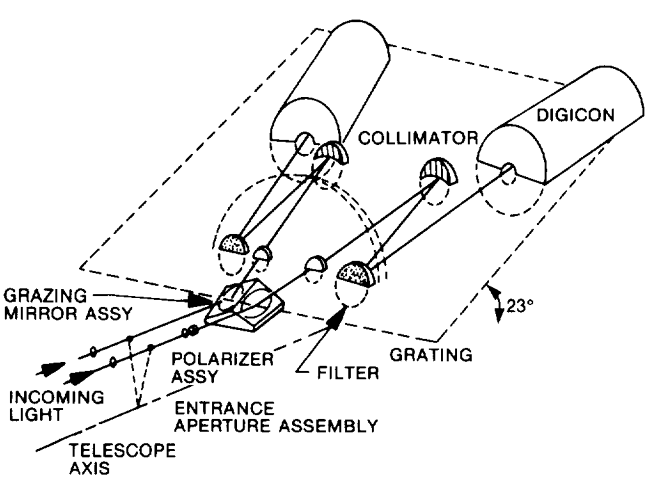


Figure 3-12 Optical Path, FOS

Time-resolved operations are used for objects with radiation that pulses at reliable periods, from 50 microseconds to 100 seconds. The specified FOS detector takes samples during each "on" period, for a number of periods, with the data added together later.

Time-tagged and rapid-readout operations study objects with irregular pulsations. For time-tagged operations, the FOS counts the spacecraft clock until the first photon strikes the FOS detector and freezes the count. Rapid-readout, on the other hand, accumulates incoming data but produces frequent readouts, up to every 20 msec, to capture start and stop points of the pulsations.

Spectropolarimetric operations measure the polarization of light to test for magnetic effects. The light passes through the polarizing analyzer and a combination of polarizing plates and prisms. These separate the light into different polarizations, each of which can be measured and compared. See Section 3.2.4.4 for one application of spectropolarimetry.

3.2.3 Faint Object Spectrograph Specifications

Table 3-2 Faint Object Spectrograph Specifications

FAINT-OBJECT SPECTROGRAPH	
Weight	680 lb (309 kg)
Dimensions	3x3x7 ft (0.9x0.9x2.2 m)
Principal Investigator	R.J. Harms, U. of Cal., San Diego
ContractoR	Martin Marietta
Apertures	0.1-4.3 arcsec^2
Resolution	250; 1300
Magnitude Range	19-26 m_v
Wavelength Range	1100-8000 Ang.

3.2.4 Observations

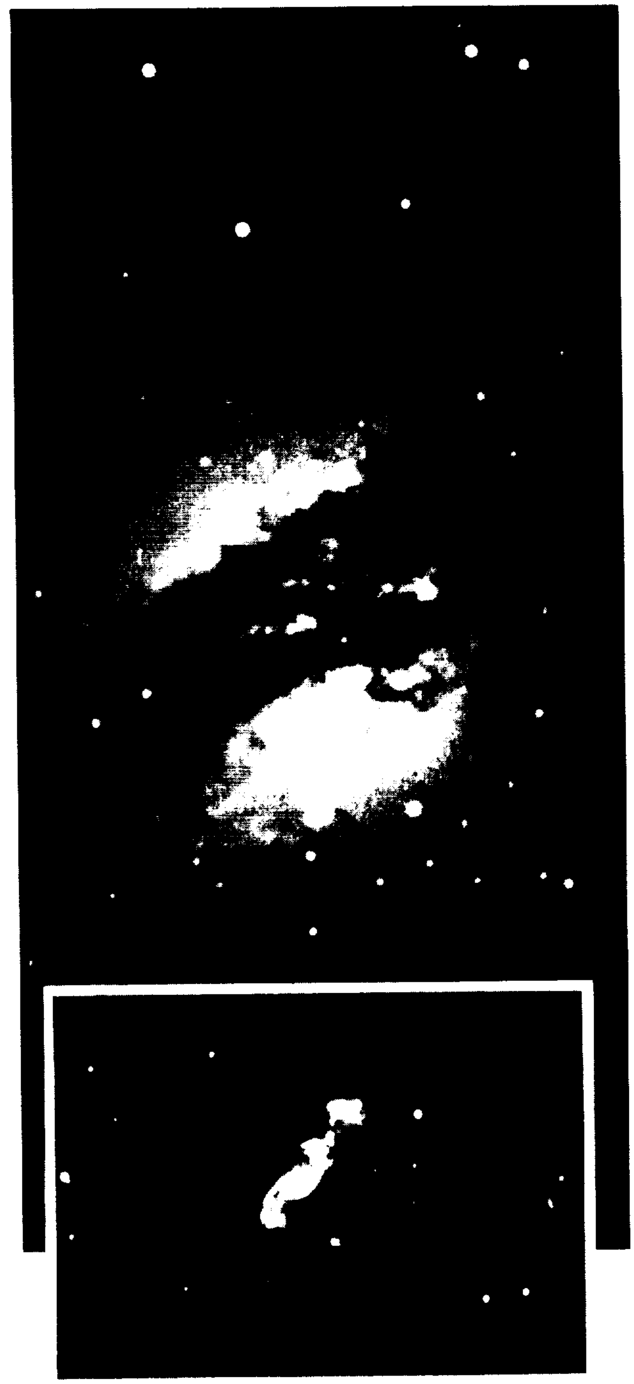
The FOS will observe many of the objects being targeted by other SIs, but for different information. Three observation plans being considered would study galaxy formation, how supernovae can be used to test distance formulas, and the composition and origin of interstellar dust.

3.2.4.1 Explosive Galaxies. Astronomers theorize that quasars, exploding Seyfert galaxies, and the Milky Way galaxy may be related as stages in galactic development. The FOS will examine quasars and exploding galaxies like the Seyferts searching for relationships.

Astronomical data from quasars indicate that they repeatedly expel nebulous clouds of gas, which expand rapidly as the entire quasar recedes from us at speeds approaching that of light. Extremely distant quasars are nearly 14 billion light years away. Astronomers believe these distant quasars may have existed since the earliest formative stages of the universe. If so, nebulous matter surrounding these quasars could be the beginning of galactic development.

Exploding galaxies, such as Seyferts and giant elliptical galaxies, bear a resemblance to quasars in the pattern of nebulosity thrown off from the center. Seyferts emit vast, hot gas clouds that are expanding at high velocities, much like the nebulous clouds of a quasar. At least one elliptical exploding galaxy, M87, may also have quasar-like jets of matter spewing from the core. Figure 3-13 shows two examples of exploding galaxies.

The FOS team will study these energetic sources, and the gas clouds they eject, looking for chemical and physical relationships that relate these earlier galaxies to the Milky Way, with its whirling, nebulous arms. Figure 3-14 is an artistic comparison of the four types of galaxies: quasar (top left), Seyfert (top right), elliptical (lower left), and the Milky Way (lower right).



Courtesy National Optical Astronomy Observatories.

Figure 3-13 Two Examples of Exploding Galaxies

3.2.4.2 Supernovae and Distance. Supernovae are dramatic evidence that the universe is violently active. A supernova is the last, explosive gasp of a dying star such as a red giant. Once the supernova erupts, most of the star's

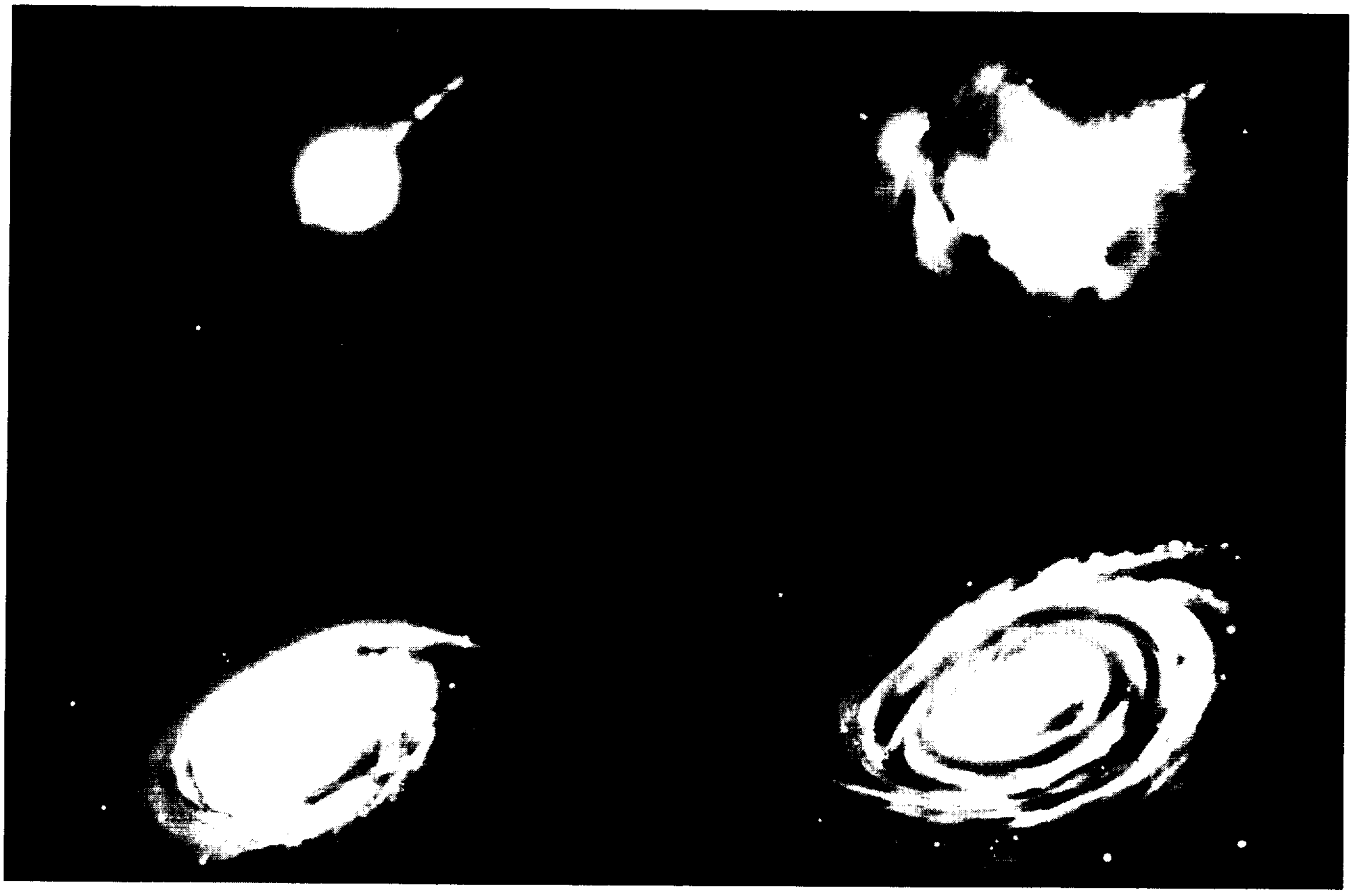


Figure 3–14 Comparison of Four Galaxy Types

remaining matter scatters into the heavens, leaving behind a dwarf star. Astronomers, however, don't know the exact details of a supernova explosion.

With the FOS spectrophotometer, astronomers can examine supernovae to measure luminosity practically as the nova occurs and periodically thereafter. Luminosity determines absolute magnitude, which is compared with apparent magnitude to calculate the distance to the supernova.

Astronomers can then compare the distance determined by the magnitude measurement against the Hubble Law to better estimate the value of the Hubble constant H. A conclusive answer requires the study of many supernovae with the Hubble Space Telescope.

3.2.4.3 The Evolution of Stars. A planetary nebula is a remnant of a supernova. It grows large and cool until stellar forces blow the star's atmosphere into space as an expanding shell of gas encircling the dying star. See Figure 3-15.

A nebula provides astronomers with a subject for studies of ultraviolet light that will yield accurate temperature, chemical, and mass analyses of the material producing the light. The FOS will study distant planetary nebulae as faint as $22m_V$, and nearby nebulae in the Large Magellanic Cloud. This particular comparison will provide a portrait of stellar evolution from different eons in the history of the universe.

Palomar Observatory Photograph.

Figure 3-15 A Planetary Nebula

3.2.4.4 The Composition of Interstellar Matter. One element of the interstellar medium — the cloud-like material in space not gravitationally attached to a star — that remains unstudied is the dust. The reason for this is that the dust particles are invisible to ground-based telescopes. Astronomers theorize that the dust collects in great magnetic fields because light filtering through the dust clouds becomes polarized — evidence of strong magnetism.

The FOS can measure ultraviolet light passing through dust clouds, looking for clues to the chemical composition of the dust and its magnetization. Astronomers hope these studies produce abundant findings about the star formation process.

3.3 THE GODDARD HIGH RESOLUTION SPECTROGRAPH

Ultraviolet (UV) radiation from objects will tell astronomers using the Hubble Space Telescope much about the composition, temperature, and density of stellar objects and the vast gas clouds throughout the universe. The scientific instrument designed for ultraviolet observation is the Goddard High Resolution Spectrograph (GHRS). Developed by Goddard Space Flight Center, under the direction of J. C. Brandt, it was built by Ball Aerospace Systems.

Ultraviolet rays rarely pierce the earth's atmosphere but have been examined before from observatories in space, most recently by the International Ultraviolet Explorer (IUE) satellite. The GHRS is more sensitive to faint objects than the IUE, to $17m_V$, though not as sensitive as the FOS. Much more importantly, the GHRS is far more accurate and has greater spectral resolution than the IUE.

3.3.1 Comparison with Faint Object Spectrograph

The two spectrographs overlap in some functions, such as measuring stars and gas clouds in the ultraviolet. But they also serve separate and valuable functions because they differ in sensitivity and spectral resolution. The GHRS can resolve extremely small differences between spectral lines, up to a spectral resolution of 100,000, but only for objects $13m_V$ and brighter. The FOS is more limited in resolution but detects far fainter objects, down to $26m_V$.

For a broad spectrum and a variety of star distances, the FOS stands out. The GHRS, on the other hand, will produce compositional information unprecedented in spectral detail.

3.3.2 Physical Description

The GHRS also is aligned parallel to the HST optical axis. Sized at 3 x 3 x 7 ft (0.9 x 0.9 x 2.2 m) and 700 lb (318 kg), it contains an optical system that produces spectra, support electronic and thermal systems, and a structure housing the enclosed systems. The SI C&DH unit handles the GHRS computer functions.

The optical system contains two apertures, a rotating carrousel with gratings to separate the wavelengths, mirrors to place the light into a specific detector, and two Digicon light detectors, one for 1050 to 1700 Å, the other for 1150 to 3200 Å. See Figure 3-16 for the GHRS structure and optical system.

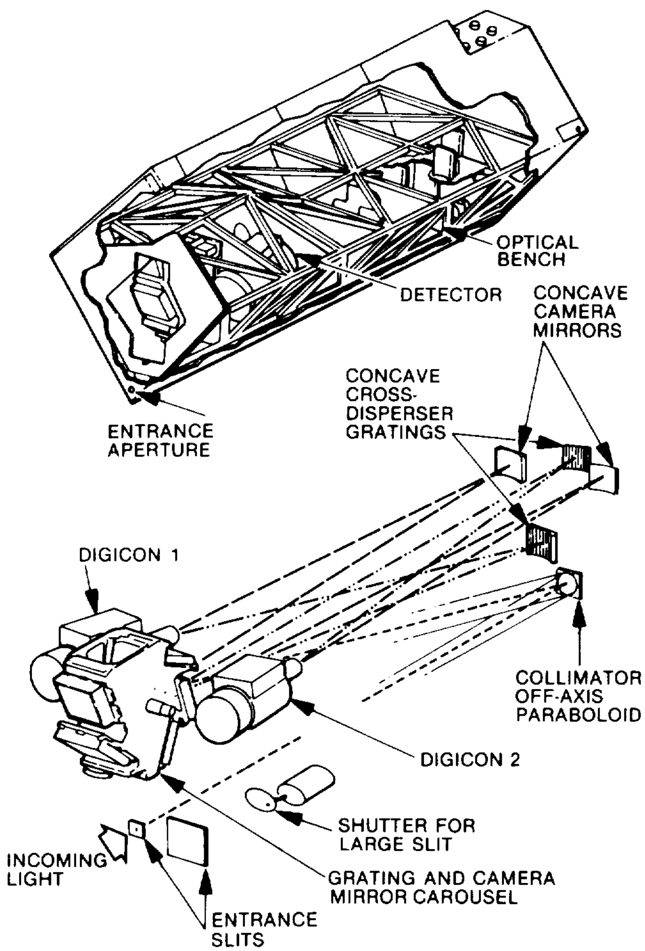


Figure 3-16 GHRS Structure and Optical System

3.3.2.1 Apertures. The GHRS has two apertures, a large science aperture measuring 2.0 arcsec across its field of view, and a small science aperture that measures 0.25 arcsec across the FOV. The apertures are not on the HST optical axis, so the light coming through each aperture is astigmatic. To adjust the divergent focal points of the light, each aperture has two slits set at right angles so the incoming lights merge again.

The large science aperture is used to locate the target, observe galaxies, and perform spectrophotometric and spectrographic observations when precise spectral resolution is not required. The small science aperture captures the full light of single objects, such as a star, and is used to obtain the GHRS maximum specified resolution of 100,000. This means that in the 2000 Å range the GHRS will display spectral features separated by 0.02 of an angstrom. When the small aperture is operating, a shutter blocks the large aperture.

Two slits in the GHRS aperture area provide wavelength calibrations. To measure accurately the wavelength of incoming starlight, the GHRS needs standards for comparison. Lamps in the instrument shine UV light through the two slits, and these wavelengths can be measured precisely. These wavelengths are called calibration standards. They are compared with incoming starlight to produce very accurate UV wavelength readings. These measurements, in turn, will provide a crucial step in calculating the composition of stars and the speed with which they move toward or away from us.

The incoming light reflects off a collimating mirror that directs the beam onto the carrousel.

3.3.2.2 Carrousel. The carrousel is a rotating wheel with seven diffraction gratings and three acquisition mirrors, used to select specific wavelengths. An encoder and motor rotate the carrousel, through coarse and fine positioning steps, to direct a desired wavelength to a detector. The carrousel motion is accurate to within 0.03 arcsec. The carrousel can move in either direction to position the right grating or mirror. See Figure 3-17.

The carrousel has three mirrors, with four settings, used to lock the HRS onto the desired object. Two settings reflect faint objects with no diffraction. The other two settings allow bright

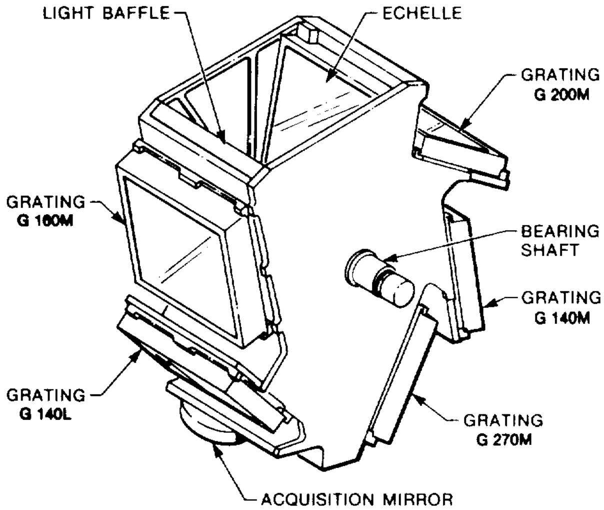


Figure 3-17 GHRS Carrousel

objects, up to -1mv, to be targeted. The latter settings moderate the brightness so that the sensitive detector diodes are not overloaded.

Each of the seven carrousel gratings spreads out the incoming light into separate wavelengths for analysis. GHRS gratings can be selected to observe the UV spectrum with low (2000), medium (20,000), or high (100,000) spectral resolution. The highest spectral resolution is obtained with two echelle gratings, where the GHRS can discriminate between spectral features as close together as 0.02 Å.

As the resolution increases, the portion of the overall spectrum in one frame decreases. For example, Grating G140M displays a spectral range just 29 Å wide, while Grating G140L displays a spectral band 290 Å wide. Table 3-3 details the spectrum covered by each grating.

Figure 3-18 illustrates the tradeoff between spectral resolution and brightness. Brightness is measured by the number of electrons striking the detection diodes per second for a particular wavelength range. The more electrons counted per second, the more intense the source for that wavelength band. However, as spectral resolution increases, the intensity decreases and the electron count drops. This means that at higher spectral resolution a celestial object must be studied longer to collect enough energy to record.

The spectral resolution of the sample spectral frames depicted ranges from 2000 (top) to 20,000 (middle) to 100,000 (bottom). The number of spectral features measured in the range between 1475 and 1480 Å increases dramatically as the wavelength range shortens.

The grating or acquisition mirror chosen on the carrousel sends the light to concave camera mirrors, which focus the dispersed grating light or the collected targeting light onto the appropriate detector.

3.3.2.3 Cross-Dispersers. Two special concave gratings, called cross-dispersers, pass along the highly resolved reflection from the echelle gratings. Diffracted wavelengths cast many light orders – similar to light "ghosts" reflected on a TV screen. All these orders can overlap if placed on the same horizontal spectrum, which would make the data unreadable. Since the echelles reflect lower orders only, it is important to keep the orders separate. So the cross-dispersing gratings place each light order

Table 3-3 GHRS Grating Spectral Ranges and Spectral Resolutions

MODE	WAVELENGTH RANGE (Å)	SPECTRAL ORDER(S)	SPECTRAL RESOLUTION ($\times 10^4$)	WAVELENGTH AMOUNT COVERED IN ONE FRAME (# OF Ås)
MEDIUM RESOLUTION				
G140M	1100-1700	1	1.8-3.0	27-29
G160M	1150-2100	1	1.5-3.0	33-36
G200M	1600-2300	1	1.8-2.7	38-41
G270M	2200-3200	1	2.1-3.3	45-49
LOW RESOLUTION				
G140L	1100-1700	1	0.15-0.22	290-291
HIGH RESOLUTION				
ECHELLE A	1100-1700	53-33	8.0-10	5.5-9.5
ECHELLE B	1700-3200	33-18	8.0-10	8.5-17.9

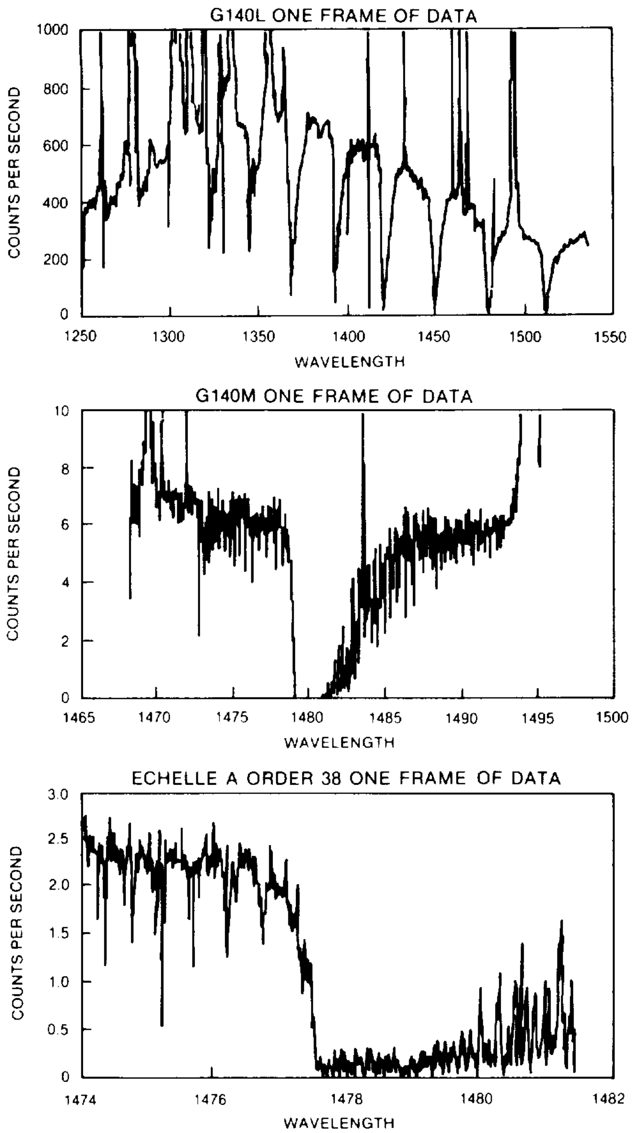


Figure 3–18 Data From Three Grating Settings

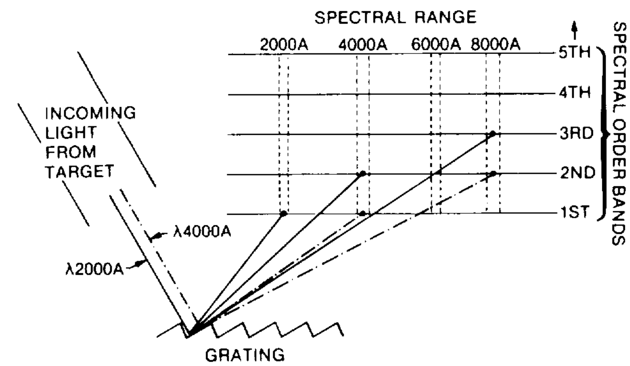


Figure 3-19 Cross-Dispersal of Wavelength Orders

on parallel horizontal bands — all first orders on one band, all second orders on another, and so on. Then scientists can examine any light order they want. Figure 3-19 illustrates the cross-dispersal technique.

3.3.2.4 Digicon Detectors. The Digicon detectors are photocathode tubes that count the photons in the incoming light. Each Digicon has a maximum wavelength range to which it is sensitive: 1400 Å for Digicon 1; 2000 Å for Digicon 2. Each tube contains a photo-sensitive window, a magnet focus assembly that accelerates and focuses the incoming electrons, 500 diodes arranged in a line to record the spectral data, and preamplifiers to transmit the data electronically. Twelve extra diodes aid in focusing and also monitor background and unwanted light. A magnetic deflection system can shift the incoming bombardment of photons horizontally or vertically across the diodes to concentrate on particular bands of the spectrum or resolve one band more clearly. See Figure 3-20.

Photons strike the window of the Digicon and project electrons inward. The electrons are accelerated in the magnetic field and land on the diode array. Each diode counts the electrons hitting it as one event. The signal goes to the amplifier, then to an accumulating device that records all diode pulses. This information is relayed either immediately or after data build up over a preset exposure time. The magnetic deflection system can re-align shifted data to compensate for the motion of the Space Telescope.

Data from the GHRS detectors go to the accumulators in SI C&DH memory. Then the information passes through the SI C&DH formatter and to the ground for analysis. If no communication with the STOCC is available, data are stored in the HST on-board science tape recorders.

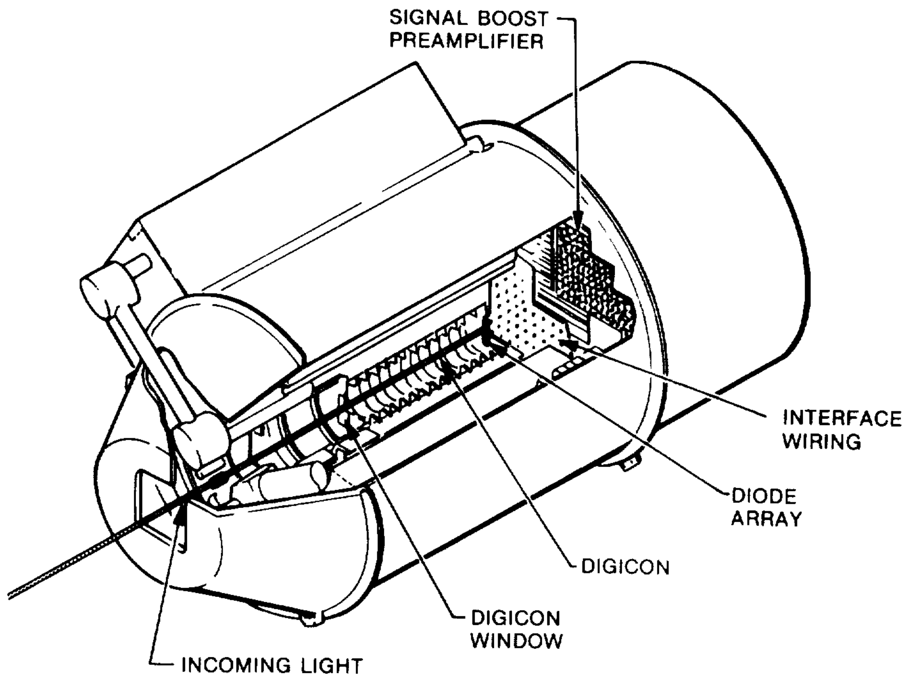


Figure 3–20 The GHRS Digicon Detector

3.3.2.5 GHRS Software. The GHRS observation control software is not in the unit itself, but resides in the NSSC-I computer in the Scientific Instrument Control and Data Handling unit (SI C&DH). The GHRS software includes seven programs for operational phases:

- Observation set-up – on command, selects the GHRS detector and aperture, rotates the carrousel to the correct setting, and sets exposure time for the upcoming observation.
- Targeting – searches for and pinpoints a target by sending pointing maneuver requests to the SSM pointing control system.
- Mapping – maps the field of view and sends the data to the STOCC if commanded.
- Data collection – controls the detector magnetic field, collects diode data, stops observations that exceed under/overexposure limits, compensates for vehicular motion for high-resolution lights, and checks the quality of incoming data.

3.3.3 Operational Modes

The High Resolution Spectrograph has two basic operational modes: target acquisition and science data acquisition.

Target Acquisition. This mode uses the large science aperture to lock onto the target and make the necessary adjustments to repoint the HST and place the target light into the small aperture. The basic targeting procedure centers the target in the large aperture and measures its location relative to a brighter object. Then the target is centered in the smaller aperture by small HST maneuvers, using the brighter object as a guide. Different acquisition mirrors are selected for specific targets.

The observer also can use two variations of the target acquisition mode. One first takes an image of the target with the Wide Field/Planetary Camera before using the large GHRS aperture to find the target. Having the large

WF/PC image helps the GHRS locate a difficult target, such as one surrounded by neighbors of similar brightness, which could confuse on-board target searches.

The other target-acquisition variation uses the field of view of the large GHRS aperture to map the sky, up to a (10 arcsec)^2 field. This acquisition aid takes less time to process than a WF/PC image, but it covers less sky.

Finally, if the observer knows the location of the target, or precision centering of the target is less important, the GHRS can be pointed blindly. Examples would be a repeat observation, with known target calibrations, or studying extended objects like galaxies, where any segment of the object will do.

Data Acquisition. There are two ways to acquire science data using the GHRS: accumulation mode and rapid readout (direct) mode.

Accumulation of data is the normal method used for gathering GHRS spectral information. The GHRS software accommodates this mode, monitoring lengthy observations for consistent quality and sudden interruptions. Time can be seconds, minutes, or hours, and the software can react to interruptions, such as the earth blocking the target, by pausing the observation and resuming it after the interruption has past.

Rapid readout provides data for a very short observation time, generally between 50 msec and 13 seconds. After each time period the individual block of data goes directly to the ground for analysis as the next time period begins. Data can be stored in on-board recorders, but the information bypasses the SI C&DH computer.

3.3.4 Goddard High Resolution Spectrograph Specifications

Table 3–4 Goddard High Resolution Spectrograph Specifications

GODDARD HIGH-RESOLUTION SPECTROGRAPH	
Weight	700 lb (318 kg)
Dimensions	3x3x7 ft (0.9x0.9x2.2 m)
Principal Investigator	J.C. Brandt, NASA/GSFC
Contractor	Ball Aerospace
Apertures	2 arcsec^2 target, 0.25 arcsec^2 science
Resolution	2000-100,000
Magnitude Range	17-11 m_v
Wavelength Range	1050-3200 Ang.

3.3.5 Observations

The GHRS resolution of ultraviolet radiation will prove useful in examining a number of celestial objects:

- Atmospheric composition and dispersion
- Content of the interstellar medium
- Star formations and binaries
- Studies of quasars and other extragalactic objects

3.3.5.1 Atmospheric Composition and Dispersion. The chemical composition of the atmosphere of stars, and of the surrounding matter, is a question long debated by astronomers. The GHRS may provide answers by studying spectral data for atmospheric composition. Chemical elements in the atmosphere have unique wavelength patterns that can be identified using the GHRS.

One such study may focus on Zeta Aurigae, a cooling red giant star. Material is being pulled from Zeta's atmosphere to an unseen companion astronomers believe may be a younger, hot star. The GHRS will study the escaping atmosphere to analyze its chemistry.

In another example closer to home, the moon of Io, orbiting the giant planet Jupiter, still has volcanic eruptions that, by earth standards, are monumental: they expel material as far as 200 miles from Io's surface. The material then breaks apart and is charged electrically by particles in Jupiter's magnetosphere. Jupiter's rotating magnetic field pulls this material into a ring around Jupiter — parallel to and surrounding Io's own orbit. This orbiting material is called a torus ring. This extremely hot, invisible ring of gas, with sulphur, sodium, and oxygen elements, has ultraviolet spectra and can be observed by the GHRS. The instrument can also examine the gases expelled from Io through volcanic action. Figure 3-21 is an artist's concept of what the torus ring would look like if it were visible.

3.3.5.2 Content of the Interstellar Medium. The GHRS can examine interstellar clouds to determine their composition. For example, the arms in spiral galaxies are thought to be waves of compressed gases. Using the highest spectral resolution over extended periods, the GHRS can study the spiral arms looking for telltale high-pressure areas, indicated by the intensity of the spectral lines (the greater the pressure, the more intense the spectral line).

In addition, starlight passing through the spiraling gas will produce spectra with certain wavelengths missing because of light absorbed by the gas. By analyzing the missing spectra, called absorption lines, astronomers can calculate the chemical makeup of the galaxy arms. The width of the absorption lines will reveal the temperatures of the elements in the arms. See Figure 3-22 for a sample spectrum with absorption lines.

3.3.5.3 Star Formation and Binaries. Eclipsing binary stars offer intriguing targets for the GHRS. Epsilon Aurigae, a yellow-white star of the third magnitude, also has an invisible companion. This companion eclipses Epsilon every 27 years, for an unusual duration of almost two years, far longer than most stellar eclipses. Epsilon Aurigae's spectral lines never change before, during, or after the eclipse, though they should if the star's light is blocked by its companion. The dark companion could not have the same spectral composition as Epsilon or astronomers would have seen it. Is it translucent? A ring of asteroids? Is it a pair of stars, or a black hole, or a protostar in birth, hidden by a thick cloud of dust and gas that still allows Epsilon to shine through? Figure 3-23 is an artistic rendition of one of these possibilities.

Only years of high-resolution observations by the GHRS may piece the clues together and identify the dark companion.

3.3.5.4 Quasars and Extragalactic Observations. Quasars are among the most violent entities in the universe, spewing out energy far greater than their estimated mass can produce, based on current knowledge. One theory speculates that a quasar center is a gigantic black hole that is pulling stars, globular clusters, and gas clouds into its vortex. As the matter nears the hole, there are massive collisions and nuclear explosions, and the density of this stellar crunching produces the extraordinary outpouring of energy. Figure 3-24 is a dramatized depiction of a quasar center.

Some quasars are close enough that the GHRS can study the ultraviolet spectral lines at the quasar center. From regular observations, the GHRS can determine at what velocity matter is ejected from the quasar center. This observation is likely to be in conjunction with other scientific instruments studying the quasar center simultaneously.

Figure 3–21 Io's Hot Torus Ring

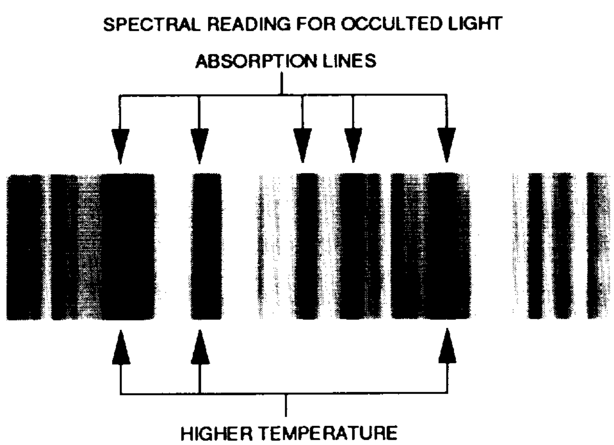


Figure 3–22 Spectrum with Absorption Lines

3.4 HIGH SPEED PHOTOMETER

The High Speed Photometer (HSP), also positioned parallel to the HST optical axis, measures the intensity and color of light, and any variation in that intensity observed over periods as short as 10 microseconds. It can measure light from ultraviolet to infrared. This gives the HSP opportunities to:

- Precisely measure the brightness of stars
- Test theories about black holes by looking for surrounding disks of gas
- Search for visible pulsars, until now observed mostly by the radio waves emitted.

3.4.1 Physical Description

The High Speed Photometer, compared to the other instruments, is relatively simple in mechanical design and has no moving parts. A filter, for example, is chosen by moving the ST rather than by moving a filter wheel within the HSP.

Figure 3–23 Epsilon Aurigae (right) and Mystery Companion

The HSP is the same size as the other axial SIs, 3 x 3 x 7 ft (0.9 x 0.9 x 2.2 m), but it weighs only 600 lb (273 kg). Its main structure is a box beam running the length of the instrument. Power, electronics, thermal, and communication subsystems are mounted on bulkheads. The heart of the instrument is the optical detector subsystem, located in the forward end of the HSP structure. See Figure 3-25 for the overall configuration.

3.4.1.1 Optical Detector Subsystem. The optical detector system consists of four entrance holes in the forward bulkhead, directly in front of four filter/aperture assemblies. Four light dissectors, one photomultiplier detector, and three off-axis ellipsoid relay mirrors complete the optics. See Figure 3-26 for the layout of the optical system.

Incoming starlight from the target passes through one of the entrance holes and falls onto a particular filter/aperture assembly. Each assembly filter plate contains 13 colored filters, which isolate certain spectral ranges in the incoming light. The selected assembly directs a portion of the beam through one of three apertures, 0.4, 1.0, or 10 arcsec in diameter. The smallest aperture removes much of the background light; the medium aperture is most accurate; and the large aperture is for locating a target (see Figure 3-27).

The light passes through a filter/aperture assembly and reflects off the ellipsoid mirrors, which sharpen the light. Then the light enters an image dissector tube (IDT). Two IDTs are sensitive to light from 1600 Å to 6500 Å (ultraviolet through visible), and two are sensitive to only ultraviolet wavelengths from 1200 – 3000 Å.

Figure 3–24 Stellar Collisions Above Quasar Center (lower right)

Electrons emitted by the IDT photocathode are focused by a magnetic field into the entrance to the 12-stage photomultiplier section of the IDT, which amplifies the electron signal. The magnetic field lets the IDT amplify electrons emitted from any area of the photocathode. The sky background, for example, can be measured.

A red-sensitive photomultiplier tube (PMT) measures light in the near infrared range, close to 7500 Å. After the incoming light passes through a clear filter, a beam splitter diverts infrared light into the PMT and UV light into an light dissector tube. Red and blue light from the same object can be studied simultaneously.

The HSP also can make polarimetric measurements. Polarimetry measures the intensity of polarized light (whose electric field vibrations are confined to a certain plane). Light enters a filter assembly and through one of four ultraviolet filters overlaid with polarized material (3M Polacoat), then onto an image dissector. Polarimetry can study phenomena not accessible to photometry, such as magnetic fields and light reflected through interstellar dust.

Photometric accuracy with the HSP should be much greater than from the ground because atmospheric turbulence (which causes stars to "twinkle" and dims starlight) is eliminated.

3.4.1.2 General HSP Operation. The operation of the HSP involves selecting an object, deciding how many bands of wavelengths should be measured and for how long, and positioning the Space Telescope to take those measurements.

Once the astronomer selects an object, the Payload Operations Control Center (POCC)

HIGH SPEED PHOTOMETER

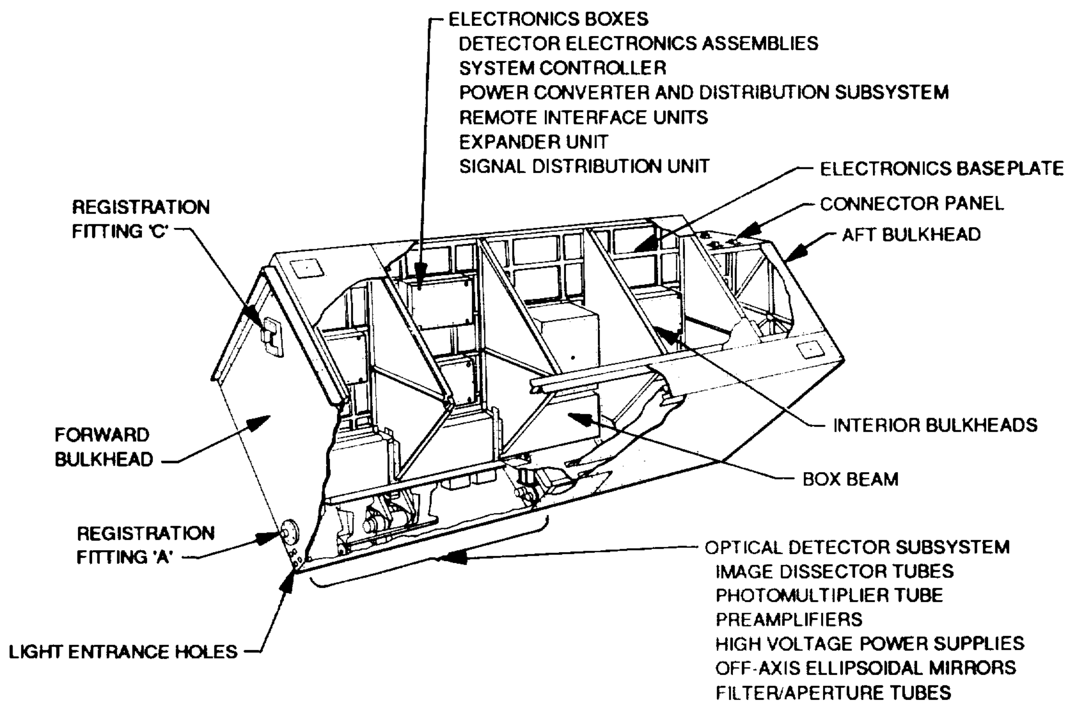
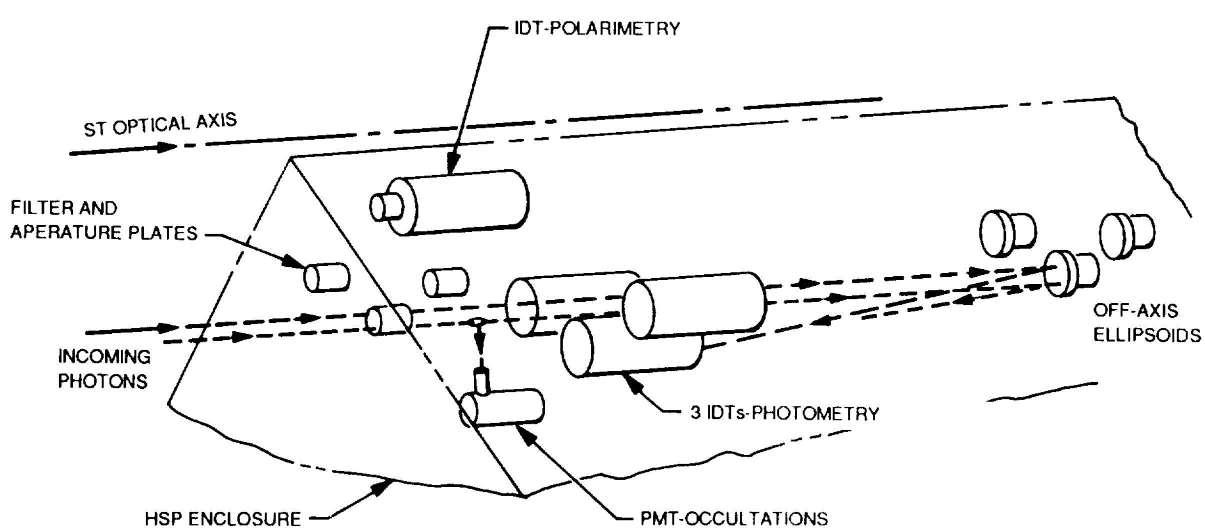


Figure 3-25 Overall HSP Configuration



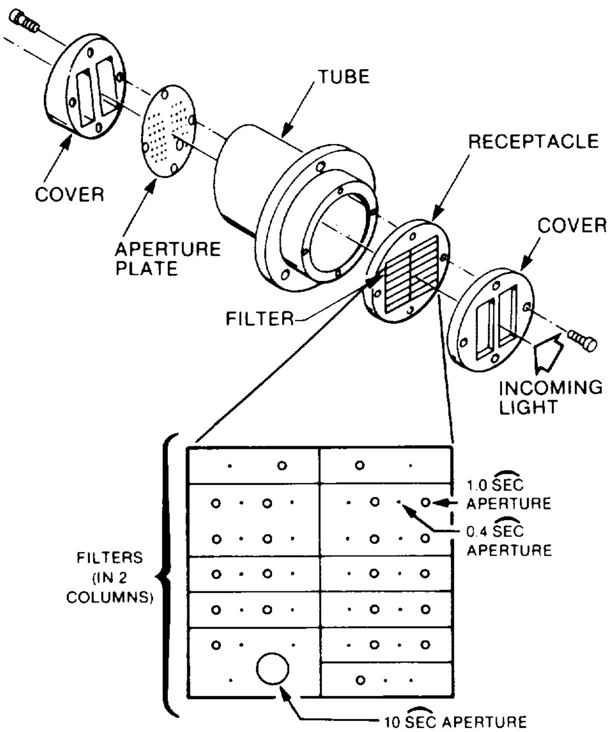


Figure 3–27 Filter/Aperture Tube, Exploded Configuration

places the software commands into the SI C&DH computer until the appropriate time, usually when the HST already is pointing in the general direction of the target after another observation. Then the software reads the commands and uses the pointing control subsystem to find and lock onto the guide stars, then onto the target.

The light passes through the 10-arcsec aperture so that the HSP can center the target. The angle of movement needed to place that light on the first filter/aperture combination is calculated by the NSSC-I. The coordinates are passed to the pointing control subsystem, and the telescope moves until the light falls onto the correct filter.

The spacecraft may repeat the small adjustments to place the light in different filter/aperture combinations. However, most filters have two pairs of 0.4 and 1.0 arcsec apertures, which can be used for simultaneous measurements (for example, primary star and background sky) without moving the HST.

The light passes through the filter/aperture and into the image dissector, which amplifies the signal and passes it, via the HSP electronic data system, to the SI C&DH. The SI C&DH sends the data to the ground or stores the information on tape for later transmission.

The number of exposures, and the length of each exposure, depend upon the brightness of the target. For example, a bright star might need only a one-second exposure for an accurate measurement, while a very faint star might require an hour exposure.

3.4.2 Operational Modes

The High Speed Photometer has several observing modes, plus a target-acquisition mode.

Targeting uses the largest HSP aperture, depending upon the image dissector chosen, to make calculations that reposition light from the target onto the correct data aperture. Astronomers can use earlier observations to help pinpoint the target, or interact with the targeting software to find the target in a crowded field of stars.

Once the target is acquired by the correct filter and aperture, the HSP can observe and measure it in several ways:

- Single-color, which uses one aperture/filter combination.
- Star-sky, which uses several apertures on one filter to capture the star's brightness and the brightness of the background sky over a period of time (minimum is 10 millisec).
- Two-IDT, which uses one IDT for star study (usually to study rapid changes in brightness) and another IDT with the same filter type to study the sky at the same time.
- Polarimetry, which uses the special polarized filter.

3.4.3 High Speed Photometer Specifications

Table 3–5 High Speed Photometer Specifications

HIGH-SPEED PHOTOMETER	
Weight	600 lb (273 kg)
Dimensions	3x3x7 ft (0.9x0.9x2.2 m)
Principal Investigator	R. Bless, U. of Wisconsin
Contractor	U. of Wisconsin
Apertures	0.4,1.0,10.0 arcsec ^{2}
Resolution	Filter-defined
Magnitude Range	< 24 m_v
Wavelength Range	1200-7500 Ang.

3.4.4 Observations

The color of starlight can disclose the temperature of a star, and the High Speed Photometer will observe stars requiring the ultraviolet sensitivity inherent in the HSP. The photometer also will provide light-intensity information to help determine stellar distances and to search for pulsars and black holes. The HSP also will observe starlight filtering through planetary atmospheres (occultation observations).

3.4.4.1 Measuring Stellar Magnitudes. Astronomers must know how intensely a star burns before they can measure its distance. The HSP can measure the intensity of light coming from even the brightest stars because it has a greater dynamic range than the faint-object instruments. Once this information is known, scientists can apply formulas to determine the luminosity and magnitude of the target star. By observing faint and bright stars, the High Speed Photometer can contribute magnitude data that astronomers can use, along with temperature or color and other data, to calculate distances to those stars.

3.4.4.2 Search for Pulsars. For nearly 20 years astronomers have been discovering objects emitting radio waves in pulses rather than steadily. These objects now are called pulsars, and their pulsations vary from every few thousandths of a second to every few seconds. Most pulsars are regular in their pattern, though some, called bursters, have irregular patterns of pulses. Astronomers have observed that most pulsars gradually are slowing down as they dissipate their energy.

Astrophysicists have created models based on theories about the origin of pulsars. One model, currently in favor, is the neutron star, the small collapsed core of a dying star, perhaps 20 kilometers across. These stars are so dense that matter exists only as neutrons. A thousand times hotter than the sun, neutron stars spin rapidly, spraying a beam of energy like a cosmic lighthouse. An artist's rendering of a pulsar is shown in Figure 3-28.

The HSP may help solve some of the mystery surrounding pulsars. Recently a few visible pulsars have been located within the magnitude range of the HSP. Astronomers hope to use the HSP's sensitivity to UV and faint visible light to capture these pulses. In addition, the photometer can record light pulses as frequently as every 10 microseconds. The HSP also can record the intensity and color of the light pulses to help determine the physical properties of pulsars.

The HSP can provide information on other light-varying, high-energy objects, like quasars and Seyfert galaxies. The latter are spiral-armed galaxies that vary in brightness. Seyfert pulsations may be caused by frequent explosions at the galaxy's center. Astronomers can extrapolate the core diameter from time variations measured by the HSP.

3.4.4.3 Occultation Observations. The HSP will record starlight occulted by atmospheric gases surrounding comet tails, stars, and Solar System planets and asteroids.

Two examples are appropriate here. The HSP can observe starlight filtered by the atmosphere

Figure 3–28 Visible Rotating Pulsar

of Titan, one of Saturn's moons. Some light wavelengths will be absorbed by the gases, and astronomers can calculate the properties of that atmosphere by the way the light dims as it passes through the atmosphere.

If light intensity varies as the light passes through a field of matter, something within that field is blocking the light. Astronomers used variation in starlight, observed over short periods of time, to discover the nine rings around Uranus. Since Voyager photographed rings with brightness variations around Neptune, astronomers hope to expand upon the Voyager discovery (see Figure 3-29).

3.5 WIDE FIELD/PLANETARY CAMERA

The most versatile of the scientific instruments is the Wide Field/Planetary Camera (WF/PC). It can produce images and spectrographic, photometric, and polarimetric measurements. The WF/PC will obtain pictures of the universe on a wider and grander scale than any other instrument to date.

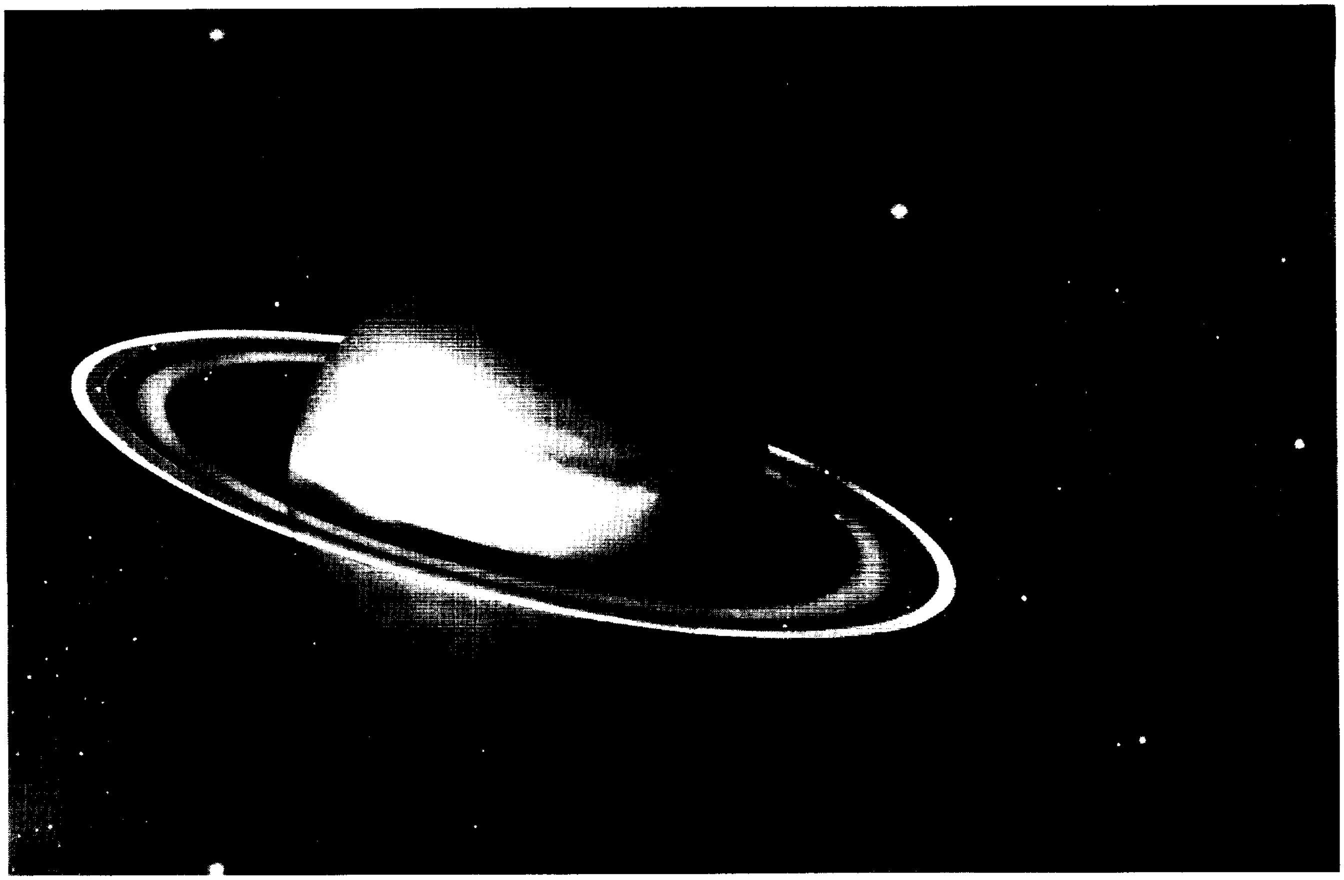


Figure 3–29 Rings Around Neptune

The WF/PC has two camera modes: wide-field camera (WFC), and planetary or closeup (PC). This is like having a wide-angle and a zoom lens on the camera. The WFC exposes a relatively wide field (for the HST; the wide-field camera still would need to take about 100 pictures to photograph the moon). It uses a focal ratio of f/12.9 with a large field of view of (2.7 armin)^2 for magnitudes down to 28m$_V$, but with limited angular resolution. The PC has better angular resolution than the WFC, separating objects that are apart by only 0.01 arcsec, but it has a smaller field of view at (66 arcsec)^2.

With these two camera modes, the WF/PC may investigate, among many things, how galaxies age, the location and shape of black holes, and the atmospheric patterns of Solar System planets.

3.5.1 Comparison of WF/PC and FOC

Having two cameras with four different functions will broaden the scope of the HST visual data. The WF/PC will take wider photographs of faint objects, without as much detail as the Faint Object Camera. The PC mode can photograph nearby objects, such as planets, that are too bright for the FOC.

The FOC distance capability is the same, but with sharper resolution. However, the FOC's maximum field of view is (22 arcsec)^2 compared to the WF/PC (2.7 arcmin)^2 field of view. The FOC, for example, can concentrate on detail within a cluster of galaxies while the WF/PC can capture the entire cluster.

3.5.2 Physical Description

The Wide Field/Planetary Camera is 3.3 x 5 x 1.7 ft (1 x 1.5 x 0.5 m) in size, with an exterior radiator that is 2.6 x 7 ft (.8 x 2.2 m). The total unit weighs 595 lb (270 kg). J. A. Westphal and the California Institute of Technology designed the camera and NASA's Jet Propulsion Laboratory built it.

The WF/PC is perpendicular to the HST optical axis, in front of the focal plane structure. A WF/PC "pickoff" mirror, in the middle of the focal pathway, reflects the center of the light beam into the camera. The spectral range of this instrument is the widest, from 1150 Å to 11,000 Å, and the resolution will allow it to distinguish between objects only 0.1 arcsec apart.

The camera is composed of an optics system; eight charge-coupled detectors (CCD) in two camera configurations, with a cooling radiator system; and a processing system to operate the WF/PC and send data to the Scientific Instrument Control & Data Handling unit. See Figure 3-30 for the overall configuration of the WF/PC.

3.5.2.1 Optics System. The optical system for the WF/PC consists of a pickoff mirror inserted in the direct line of the telescope light path; an entrance aperture with shutter; a carrousel with filters, gratings, and polarizers; a pyramid mirror to split the light; and fold and relay optics to place the lights onto the CCDs.

The pickoff mirror is centered diagonally in the light path of the telescope. The mirror deflects the central section of the beam at a 90-degree angle into the entrance aperture of the WF/PC. The shutter behind the aperture controls the length of exposure, from approximately

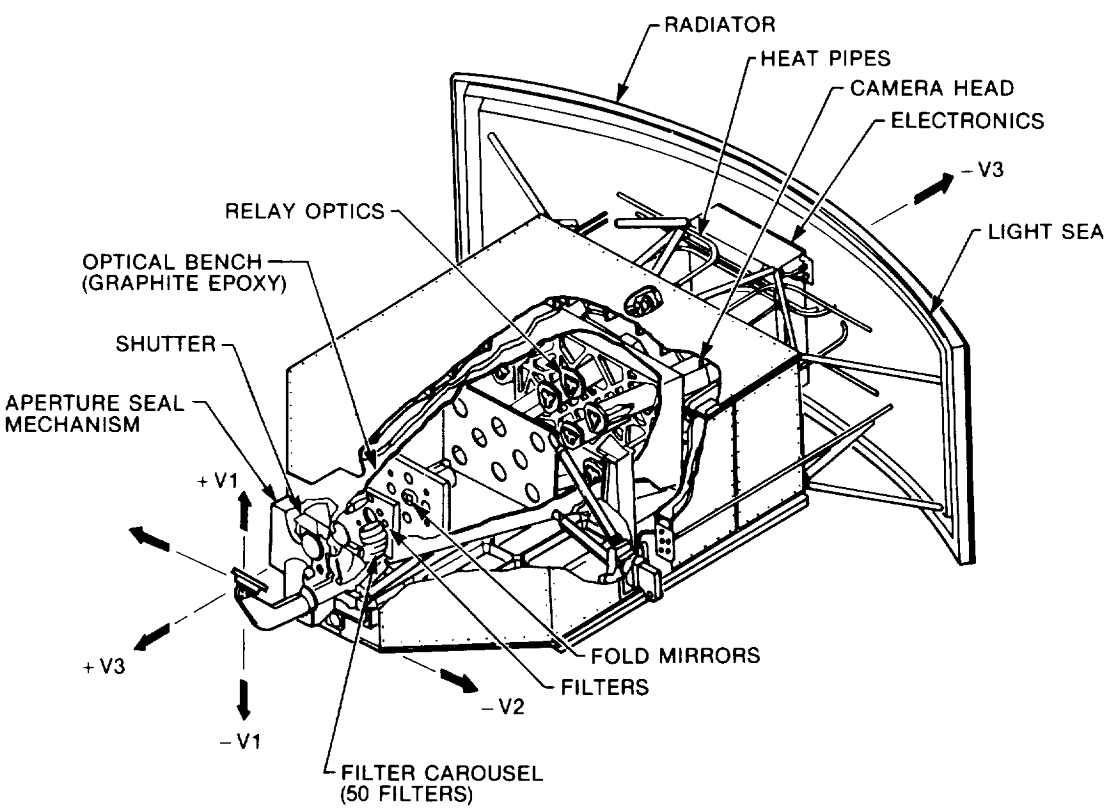


Figure 3-30 The Overall WF/PC Configuration

0.1 second to over 27 hours. A typical exposure time is expected to be 45 minutes, or roughly half an orbit around earth.

The light passes through a filter carrousel, which contains 48 filters, four clear lenses producing undispersed lights for targeting, three diffraction gratings, and three polarizers. The WF/PC can place one or several of the filters into the light path for dual functions. For example, the WF/PC can take a photograph and measure light intensity during the same exposure. The filter assembly, with its overlapping capability, makes the WF/PC the most versatile of all instruments.

At this point the decision to use either the WFC or PC mode is implemented by moving the pyramid mirror to one of two 45-degree angles. The pyramid splits the light beam into four parts, along a path that goes to a specific set of CCDs.

The light reflects from the pyramid mirror back up to fold mirrors, then down past the pyramid mirror and onto re-imaging mirrors. These focus the beam, finally, onto the selected CCD. See Figure 3-31 for a diagram of the basic optical system.

3.5.2.2 Charge-Coupled Detectors. Each charge-coupled detector is a silicon chip with an array of pixels, which are position detectors, 800 on a side. As the photons bombard the array, each pixel records an electrical charge proportional to the number of photons striking it. This will reproduce the intensity pattern of the light when the light is reconstructed later. The charge signal from each pixel then passes through the electronics system. Figure 3-32 illustrates how the incoming photons will strike the pixels of the CCD.

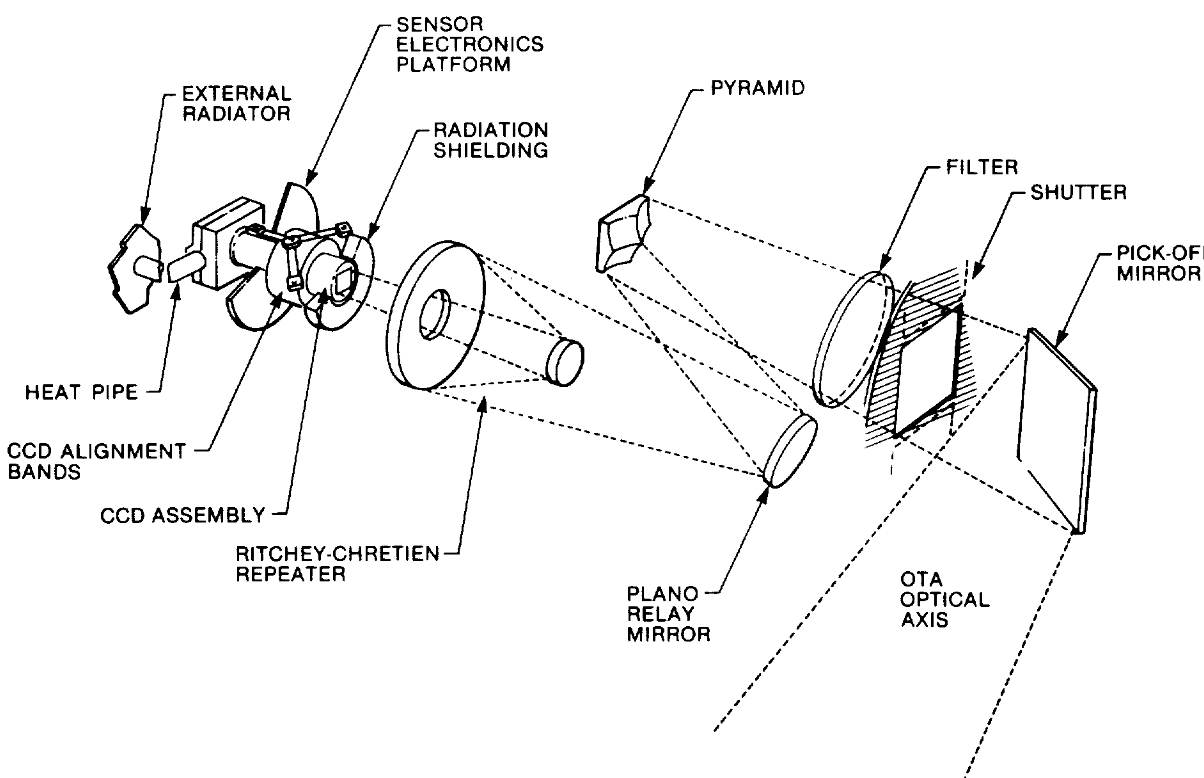


Figure 3-31 Wide Field/Planetary Camera Optics Design

The CCDs are powerful because they cover such a wide spectral range and because the signal, especially for faint objects, is uncluttered by background noise from heat and electronic interference. The spectral energy accepted is broad because each chip is coated with a phosphor that converts ultraviolet photons to visible photons. In addition, the natural sensitivity of the CCD is toward the infrared end of the spectrum. The great number of signals, 640,000 (8002) from each CCD, add to a single image when processed.

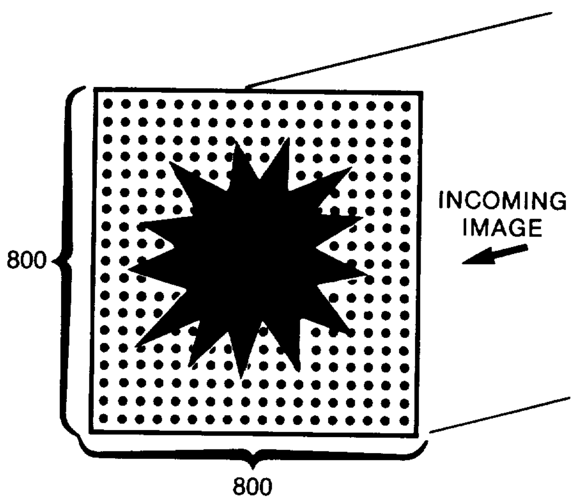


Figure 3–32 WF/PC Imaging

Heat is minimized in each CCD because the cooling system keeps the CCD temperature at a nominal –95 degrees Celsius. The cooling system consists of pipes that conduct heat from the CCDs to a radiator on the surface of the SSM. In addition, a special unit bathes the CCDs with ultraviolet light regularly to increase the CCD sensitivity to short wavelengths.

3.5.2.3 Processing System. The WF/PC has a microprocessor that controls camera operations and transfers data to the SI C&DH unit. The microprocessor sets shutter exposure time, selects the required filter combinations, rotates the pyramid mirror to select a specific camera optic path, and reads out the signals coming from the CCDs.

3.5.3 Operational Modes

The Wide Field/Planetary Camera operates as two cameras, either a wide-field or a planetary (closeup) camera. Each has a separate field of view and resolution. Target acquisition is performed using the HST guidance system and the WF/PC's generous field of view to capture the target.

Within each camera operation, there are several modes that astronomers can select to study the target. These modes include photometry, spectroscopy, and photopolarimetry. The basic operational mode is imaging, since the WF/PC records an image of the target. Because of the construction of the CCD detectors, that light beam also yields the intensity of the bombarding photons. This makes the basic mode both light-producing and photometric.

Wide Field/Planetary Camera spectroscopy uses a grating to capture ultraviolet spectra. The camera can also use filters for specific wavelength photometry, as well as for filter polarimetry in the 2500- to -8000 Å spectral range.

3.5.4 Wide Field/Planetary Camera Specifications

Table 3–6 Wide Field/Planetary Camera Specifications

WIDE FIELD/PLANETARY CAMERA	
Weight	595 lb (270 kg)
Dimensions	Camera - 3.3x5x1.7 ft (1x1.3x0.5 m), Radiator - 2.6x7 ft (0.8x2.2 m)2
Principal Investigator	J.A. Westphal, CIT
Contractor	Jet Propulsion Laboratory
Optical Modes	f/12.9 (WF), f/30 (P)
Field of View	160, 66 arcsec^2
Magnitude Range	9-28 m_v
Wavelength Range	1150-11,000 Ang

3.5.5 Observations

The Wide Field/Planetary Camera will be the busiest scientific instrument on the Hubble Space Telescope. With its variety of capabilities, the WF/PC can perform several tasks while observing a single object. For example, it can focus on an extended galaxy and take a wide-field picture of the galaxy, then concentrate on the galaxy nucleus to measure light intensity and take photographic closeups of the center. In addition, the WF/PC can perform measurements while other instruments are observing.

Specific observations for the WF/PC range from tests of cosmic distance scales and universe expansion theories to specific star, supernova, comet, and planet studies. Some important searches are for evidence of black holes, planets in other star systems, Martian atmospheric storms, and the connection between galaxy collisions and star formation. Those examples are discussed below.

3.5.5.1 Photographing a Black Hole. Black holes "hide" behind their overwhelming gravitational pull. When a dying star collapses to become a black hole, often only a few miles in diameter, the gravity of the superdense core pulls all matter into it. If a black hole is part of a binary star system, the hole also may pull gases from the atmosphere of the companion star. The gases and other elements create a swirling disk around the black hole, until, at the edge of the hole, all light disappears because of the overwhelming gravitational pull. The WF/PC will search for swirling disks as evidence of black holes. See Figure 3-33 for an artistic rendition of a blue giant-black hole binary system.

3.5.5.2 Planets in Other Systems. The Wide Field/Planetary Camera and other scientific instruments will study stars looking for planets. The WF/PC pyramid mirror has a light-blocking spot to mute some of the brightness of a star so its orbital path can be plotted against the starry background. A planet the size of Jupiter can exert enough gravitational force to make its "sun" wobble in its orbital path. The WF/PC can chart this wobble over years to generate sufficient evidence. See the Faint Object Camera for a different plan to attack this planetary search.

3.5.5.3 Martian Dust Storms. Pictures from the Mariner 9 and Viking lander spacecrafts clearly demonstrated that Martian winds sculpt the landscape, eroding the craters and mountains over time. Intense study of Martian windstorms has astronomers and geologists puzzled because the erosion predicted by these studies has not produced more dramatic evidence. For example, the craters appearing near the Viking lander should have disappeared by now, after millions of years of exposure to the winds. The WF/PC can study the wind patterns periodically to calculate more precisely how they affect the surface.

3.5.5.4 When Galaxies Collide. The process of star formation, being studied by several scientific instruments, climaxes with the gravitational collapse and nuclear ignition of gases from huge interstellar clouds. A prime example of this collapsing pattern, astronomers believe, is when two galaxies collide, illustrated in Figure 3-34.

When this happens, tremendous shock waves sweep through the gaseous spiral arms and extended lobes of the galaxies, compressing and compacting the gases. If a critical density is reached, coalesced gases explode into nuclear life as a star.

The high resolution and spectrographic capability of the WF/PC could, over a three-year periodic observation of a specific target, produce evidence of a star being born. See Figure 3-35 for an artist's conception of this birth: two galaxies approach, then collide (top), compressing gas until it ignites (bottom).

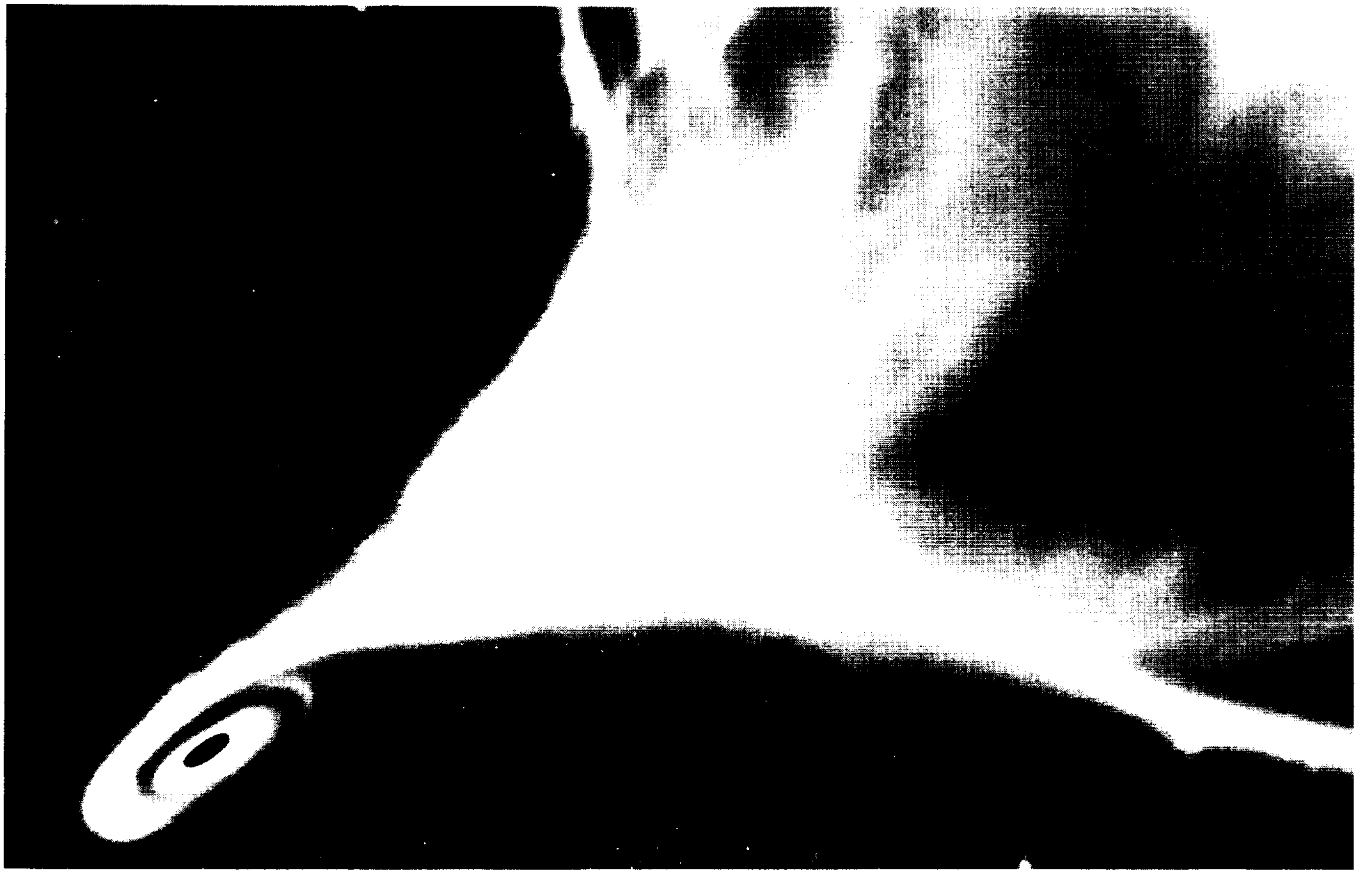
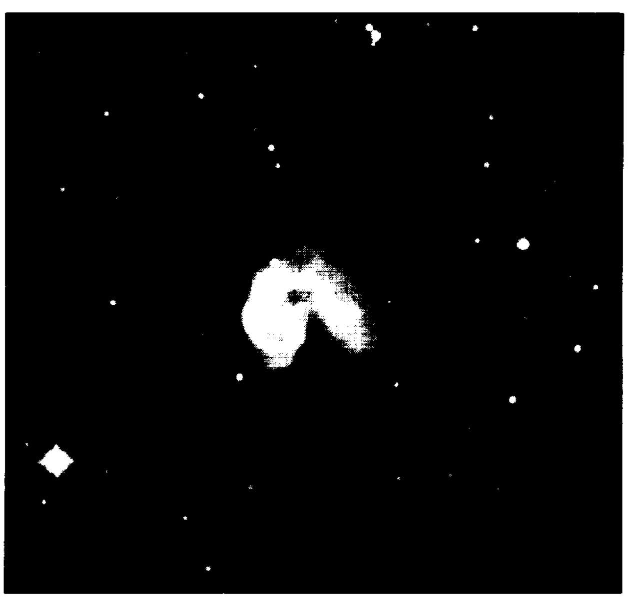


Figure 3–33 Black Hole in Binary System



Palomar Observatory Photograph.

Figure 3–34 Two Spiral Galaxies Colliding

3.6 ASTROMETRY (FINE GUIDANCE SENSORS)

When two of the fine guidance sensors (FGSs) are locked on guide stars to provide pointing information for the HST, the third FGS can serve as an scientific instrument to measure the position of stars in relation to other stars. This is called astrometry, and it will help astronomers determine stellar masses and distances.

The sensors were fabricated by Perkin-Elmer. They are located in the focal plane structure, placed at right angles to the optical path of the Space Telescope and 90 degrees apart. They have "pick-off" mirrors to deflect the incoming light into their apertures. (See 2.3, Chapter 2 for a more detailed description of the FGSs.)

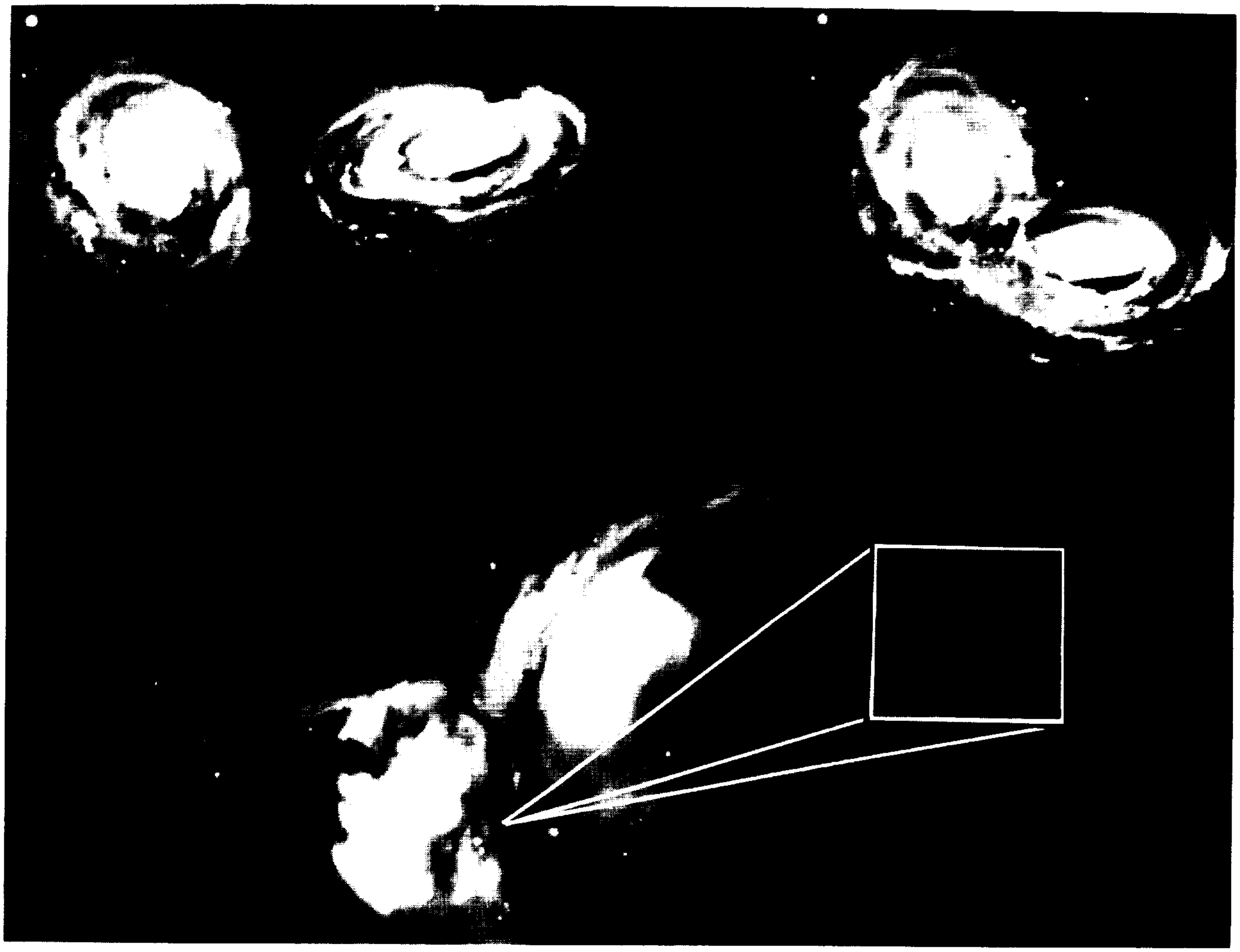


Figure 3-35 Time-Lapsed Star Birth

3.6.1 Fine Guidance Sensor Specifications

Table 3-7 Fine Guidance Sensors Specifications

FINE GUIDANCE SENSORS	
Weight	485 lb (220 kg)
Dimensions	1.6x3.3x5.4 ft (0.5x1x1.6 m)
Contractor	Perkin-Elmer Corp.
Astrometric Modes	Stationary & Moving Target, Scan
Precision	0.002 arcsec ²
Measurement Speed	10 stars in 10 min
Field of View	Access: 60 arcmin ² Detect: 5 arcsec ²
Magnitude Range	4-18.5 m_v
Wavelength Range	4670-7000 Ang.

3.6.2 Operational Modes for Astrometry

Once the two target-acquisition fine guidance sensors lock onto guide stars, the third guidance sensor can perform astrometric operations on targets within the field of view set by the guidestar positions. The sensor should be able to measure stars as faint as 18 m_V.

There are three operational modes for astrometric observations: position mode, transfer-function mode, and moving-target mode. Position mode allows the astrometric FGS to calculate the angular position of a star relative to the guide stars. Generally, up to 10 stars will be measured within a 20-minute span, which keeps the pointing stability of the guide-star

FGSs within the required accuracy of 0.04 arcsec.

The transfer-function mode measures the diameter of the stellar target, either through direct analysis of a single-point object or by scanning a diffuse target. Examples of the latter include Solar System planets, double stars visually closer together than 0.1 arcsec, and targets surrounded by nebulous gases.

Astrometric measurements of binary stars visually separated by more than 0.1 arcsec can produce measurements of stellar masses, leading to information on the importance of stellar gravity in the evolution of star and planetary systems.

Moving-target mode measures a rapidly-moving target relative to other targets when it is not possible to precisely lock onto the moving target. An example would be measuring the angular position of a moon relative to its parent planet.

3.6.3 FGS Filter Wheel

Each FGS also has a filter wheel for astrometric measurement of stars with different brightness and to classify the stars being observed. The wheel has a clear filter for guide-star acquisition and faint-star (greater than $13m_V$) astrometry; neutral-density filter for observation of nearby bright stars; and two colored filters used for estimating a target's color (chemical) index, increasing contrast between close stars of different colors, or reducing background light from star nebulosity.

3.6.4 Astrometric Observations

Astronomers measure the distance to a star by charting its location on two sightings from earth at different times, nominally six months apart. The earth's orbit changes the perceived (apparent) location of the nearby star, and the parallax angle between the two locations can lead to a estimate of the distance to the star. Stars are so distant, of course, that the parallax angle is quite small, requiring a precise field of view to calculate the angle. Even with the precision of the FGS, astronomers cannot measure distances by the parallax method beyond nearby stars in our galaxy.

There are certain stars, however, that are considered distance indicators. One such class of objects, called Cepheid variables, are notable because they expand and contract, or pulse, regularly. The frequency of these pulsations is related to the intrinsic luminosity (absolute magnitude) of the Cepheid. Astronomers can determine the distance to a Cepheid by relating the pulsation periods to apparent magnitude (how brightly the star shines), then calculating the distance.

Knowing the distance to a nearby Cepheid becomes important because astronomers can compare magnitudes between Cepheids with known distances and more faint Cepheids visible to the Space Telescope. Using this information, astronomers will calculate the distance to the faint Cepheids. In the neighborhood of those fainter Cepheids will be supergiant and regular nova stars. Astronomers can accurately measure the distance to these brighter objects from the Cepheid comparisons. Since novae and supergiants are bright than Cepheids, they are excellent "distance standards" for measuring greater distances.

Section 4
HUBBLE SPACE TELESCOPE MISSION DESCRIPTION

The Hubble Space Telescope, once deployed by the Space Shuttle, will have a mission extending at least 15 years, based on orbital maintenance. The HST program has three operational mission phases: launch and deployment operations, supported by the Space Transportation System; mission operations once in orbit, which includes the verification testing and the scientific observations; and maintenance operations over the Space Telescope's lifetime in orbit.

The first program phase, development of the Hubble Space Telescope, concludes with the launch of the Shuttle carrying the Space Telescope. Chapter 5 lists completely the organizations responsible for that phase of the HST program: Marshall Space Flight Center, for overall project management; Lockheed Missiles & Space Company and Perkin-Elmer Corp. for prime contract responsibility; and a team of instrument development teams that designed and developed the five scientific instruments.

Lockheed built the spacecraft's outer structure, the Systems Support Module, and some of the internal equipment. Perkin-Elmer built the Optical Telescope Assembly of mirrors and support structures, as well as the three fine guidance sensors. Then Lockheed assembled all the components, instruments, and optics, tested the completed Space Telescope for durability under liftoff and orbit conditions, before its shipment to Kennedy Space Center.

At Kennedy prelaunch crews prepared the Space Telescope for its flight and loaded it into the Shuttle cargo bay. Johnson Space Center coordinated mission flight plans with the Space Telescope Operations Control Center (STOCC) and trained the Shuttle astronauts for the specific in-space maneuvers and extravehicular activities that may be required once the Shuttle lifts off.

Flight operations cover the period from launch through deployment, which places the Space Telescope into orbit. The Space Shuttle will be launched from Kennedy Space Center and establish the orbit required for the Space Telescope. Then the Shuttle's remote manipulating system arm will place the HST into orbital position as the STOCC runs the deployment sequence. Finally, the Shuttle will release the Space Telescope, and the HST will begin operating on its own.

Mission operations concern the in-flight testing and operation of the Space Telescope. The spacecraft will undergo up to six months of system and instrument testing and calibration to determine the HST's ability to function for up to 15 years. Once operational, the telescope will perform observations selected and supervised by the Space Telescope Science Institute. The Payload Operations Control Center will handle spacecraft commands and operations, status-signal processing, and mission scheduling, the latter with the Institute. The liaison between the Institute and the POCC will be the Science Support Center.

During its life, the Space Telescope will operate with certain defined characteristics, such as how much time it spends in the earth's shadow each orbit, or maneuvering and viewing constraints. The Space Telescope, for example, cannot point within 50 degrees of the sun when maneuvering unless the sun is behind the earth, as viewed by the HST.

In the maintenance and refurbishment phase, the Shuttle can bring up replacement equipment on a maintenance mission, move the Space Telescope to a higher orbit, or even bring it back to earth for major overhaul.

4.1 LAUNCH AND DEPLOYMENT

The launch through deployment operation will place the Hubble Space Telescope in orbit, after checking out the HST systems. The following sections discuss the launch and deployment of the Hubble Space Telescope in detail, including planned contingencies for emergencies that could arise.

4.1.1 Launch and Predeployment

Prior to launch from Kennedy Space Center, with the Hubble Space Telescope in the Shuttle cargo bay, the Orbiter will provide power and communication for the HST. The Orbiter standard switch panel, located in the Orbiter aft flight deck, will control power to the HST until the spacecraft is deployed. Essential power to the HST will come from the Orbiter through an external power line called an umbilical, which connects to the HST aft bulkhead. The fixed-head star tracker shutters will be closed to prevent contamination during launch, and the antennas and solar arrays will be stowed. In addition, the multiple-access receivers and the rate sensing unit will be powered.

At launch, the Shuttle will lift to an orbit of 330 nmi. (607 km), plus or minus 5 miles, inclined at 28.5 degrees from the equator. Johnson Space Center's Mission Control Center, in Houston, TX, will confirm the orbit. Figure 4-1 shows the Shuttle lifting off the Kennedy launch pad.

Figure 4–1 Shuttle Lifting Off

4.1.2 Predeployment Checkout

After establishing an orbit the crew will open the cargo bay doors and expose the HST to space. Roughly two hours later the crew will start up the telemetry systems and the Orbiter payload interrogator (PI). The PI is the communication device that links the Space Telescope Operation Control Center (STOCC) and the HST. The Orbiter will send power to the HST main power buses after waiting at least four hours for the HST communication system components to depressurize. The STOCC will turn on the HST thermostatic heaters so they can keep the internal HST components above survival temperature levels as temperatures drop in space.

For the rest of the first flight day, the STOCC will turn on the data management subsystem, data interface units, tape recorders, control unit/science data formatter, pointing/safemode electronics assembly, rate gyro assemblies, and deployment control electronics. The STOCC will monitor, via telemetry, the DF-224 computer memory contents and the activated systems undergoing testing. The telemetered data go to the PI, then through the Tracking and Relay Satellite System (TDRSS) to the STOCC. Transmission will depend upon the positions of the communications satellites and the Orbiter relative to each other and to the earth's shadow. If necessary, the HST forward low-gain antenna could send telemetry directly to TDRSS.

4.1.3 Contingencies for Launch and Predeployment

4.1.3.1 Launch. The on-board Hubble Space Telescope equipment and instruments are checked out thoroughly prior to launch. Immediately before the launch, the external umbilical power line between the HST and Orbiter must be connected, and the fixed-head star tracker shutters must be closed. If there were problems in any of these areas, the STOCC would delay launch until the problem is resolved.

4.1.3.2 Predeployment. If power cannot be applied to the HST from the Orbiter umbilical prior to deployment, the crew will check the umbilical connection. If the umbilical is connected but not working, the crew can disconnect it. This automatically switches the Space Telescope to internal battery power. Because the batteries hold a charge for only about 3.5 hours, the Orbiter crew would immediately deploy the HST, holding it by the remote manipulator system (RMS) arm, and activate the solar arrays. Only then would the STOCC perform the HST system tests normally conducted before deployment. If predeployment contingencies fail, the Orbiter would return with the HST.

4.1.4 Deployment

On the second day, the crew will prepare to place the Space Telescope in space. This operation will include switching to HST battery power, lifting the spacecraft out of the Orbiter bay with the RMS, and extending the telescope solar arrays and antennas. This will complete the formal launch and deployment, and the HST will be ready for orbital verification.

4.1.4.1 Placement in Space. If the Space Telescope subsystems check out, the STOCC will begin the deployment procedure. The Orbiter crew will connect the RMS to one of the grapple fixtures on the forward shell. The RMS will lift the HST out of the Shuttle cargo bay and maneuver it to a precalculated position above the Orbiter. Figure 4-2 shows the RMS maneuvering the HST into space.

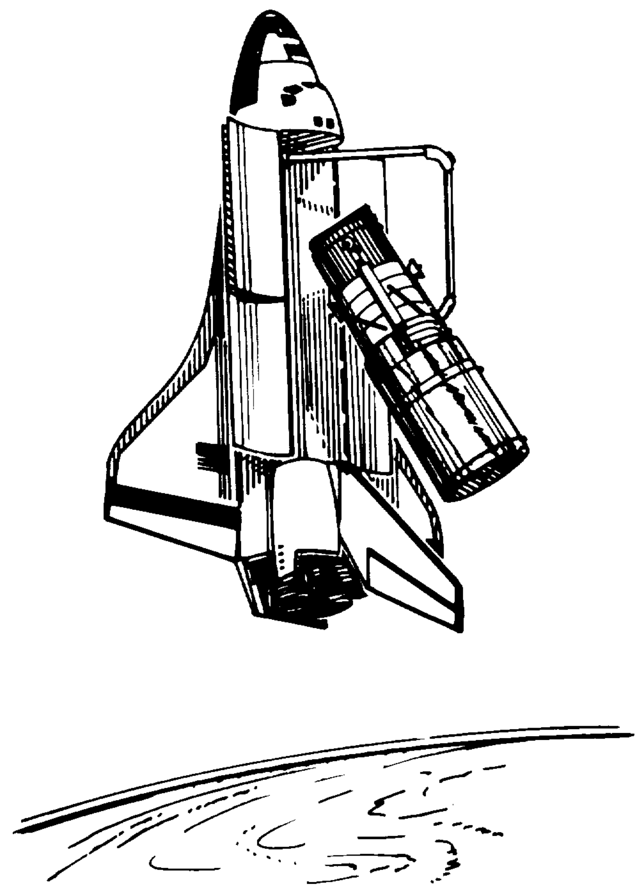


Figure 4-2 RMS Maneuvers HST

Just before placing the HST in space, the crew will switch over power from the Orbiter to the HST batteries. At the same time, from within the Orbiter the crew will turn off HST heaters to conserve power, then disconnect the umbilical, which removes the Orbiter power connection to the HST. The HST now will be on its own power, driven by the batteries until the solar arrays are deployed.

4.1.4.2 Deployment of Appendages. The STOCC must extend the solar arrays and high-gain antennas and get the HST power-accumulating and communications systems operating within 6.5 hours. The most crucial point in the deployment procedure will be the extension of the two solar arrays. For about three hours the STOCC, by remote command, will extend and test the solar arrays and antennas. The Orbiter crew, meanwhile, will give the STOCC visual confirmation and film the procedure.

The solar array deployment will involve:

1. Positioning the HST so that the solar array panels will face the sun (this could be delayed until the HST is in full sunlight) (30 min).
2. Releasing the array forward and aft latches using the SSM mechanism control unit (5 min).
3. Raising the masts with the primary deployment mechanisms (8 min).
4. Unfurling the +V2 solar array blanket with the secondary deployment mechanism (5 min).
5. At the same time, commanding the electrical power subsystem (EPS) to turn on the current charge controllers so the batteries can receive power.
6. Turning on the OTA and battery heaters again.
7. Deploying the -V2 SA blanket (5 min).

Figure 4-3 illustrates the deployment of the solar arrays.

At this point the STOCC will start the pointing control subsystem magnetic sensing system. When the crew gives visual approval, the STOCC will erect the high-gain antenna booms

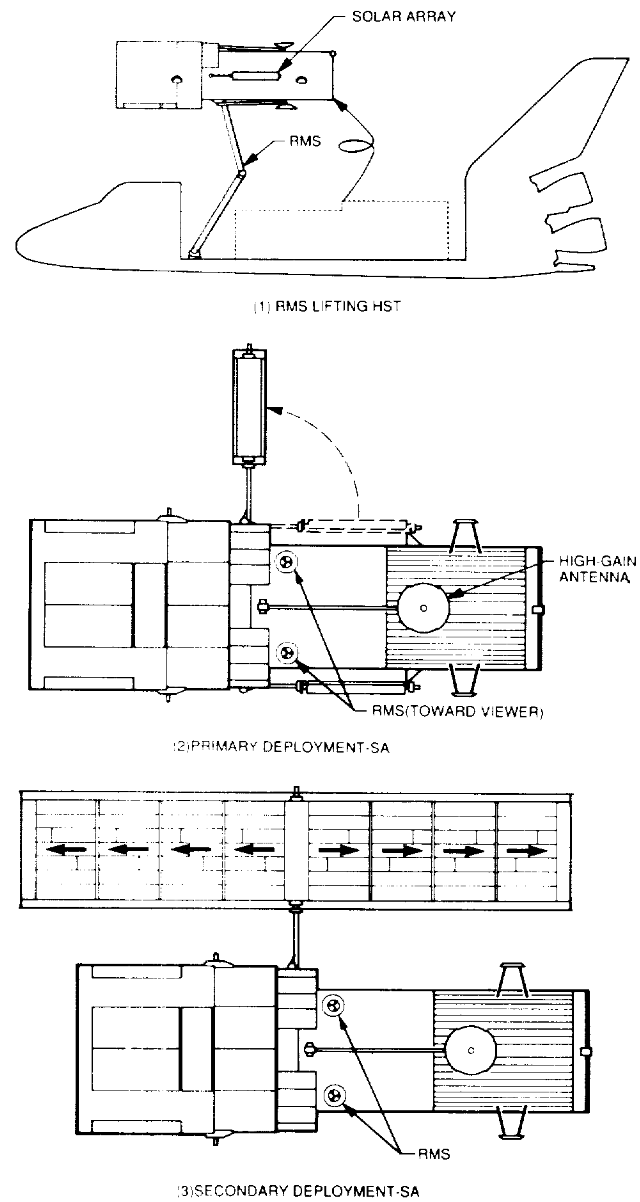


Figure 4-3 Deployment of Solar Arrays

simultaneously. This will take about 10 minutes. The aperture door latch will be released while the antennas are being extended, during a shadow portion of the orbit. The door itself will not be opened until the coarse sun sensors are operating, to protect the aperture from excessive sunlight.

The STOCC will begin slewing tests to make certain the solar arrays move and position properly. Again, the crew will give visual verification. The entire deployment procedure, because of verification tests, may take over three hours.

4.1.4.3 Release into Orbit. With the solar arrays supplying power, the STOCC begins turning on equipment not needed earlier in the deployment process.

The HST now will be ready to be released from the RMS. The RMS arm will adjust the HST into its correct attitude, and the STOCC will activate the attitude control system to monitor the spacecraft's position. Fifteen minutes later the RMS will release the spacecraft and the Orbiter will move away from the HST (see Figure 4-4).

STOCC commands now will start up the DF-224 computer's "keep-alive" monitors and begin early pointing procedures. The SI C&DH NSSC-I computer will power up. The aperture door will be opened 24 hours after the Space Telescope is in orbit.

The Orbiter will remain nearby for the next 45 hours in case of emergency.

4.1.4.4 Deployment Contingencies. Many of the deployment contingencies will use manual overrides built into the Hubble Space Telescope for emergencies. If, before deployment, the HST internal systems do not receive power immediately, the crew can turn on the power manually. The crew would go into the cargo bay, locate the astronaut control panel inside the trunnion bay of the SSM equipment section, and manually switch on internal power. HST power is vital to maintain the correct temperature. Figure 4-5 shows the crew switching on the power.

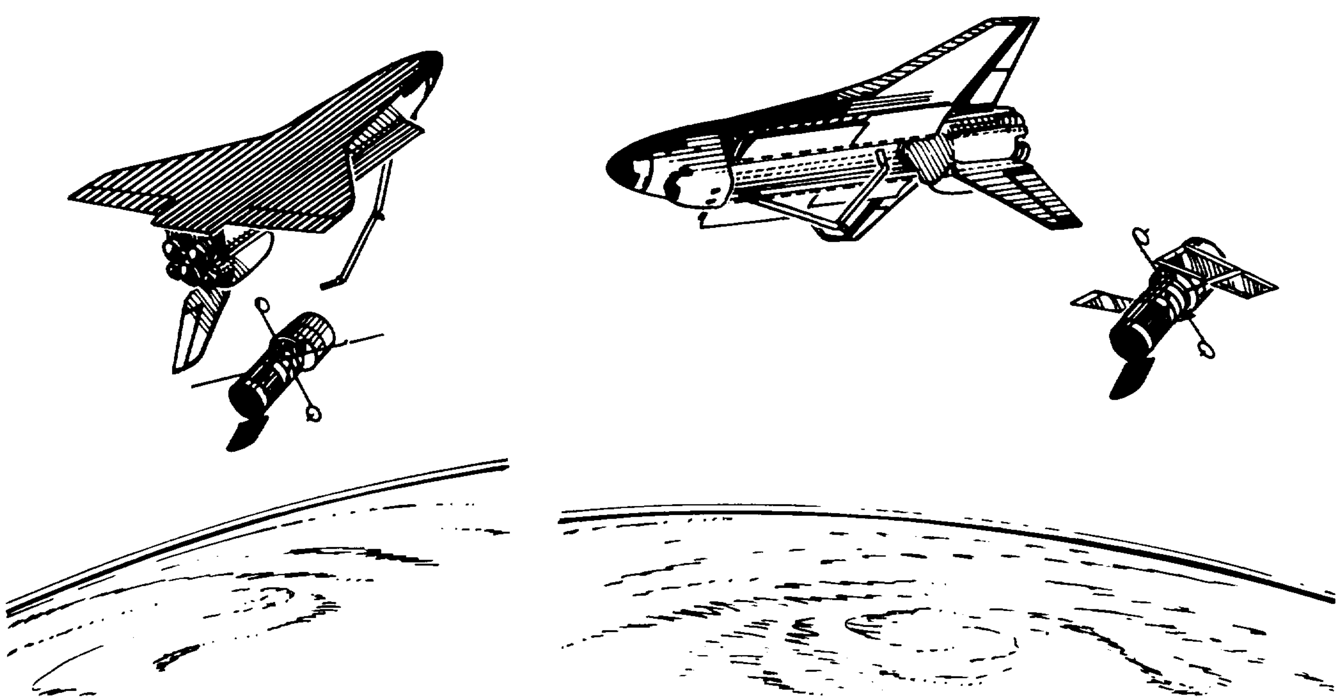


Figure 4–4 HST Released and Orbiter Moves Away

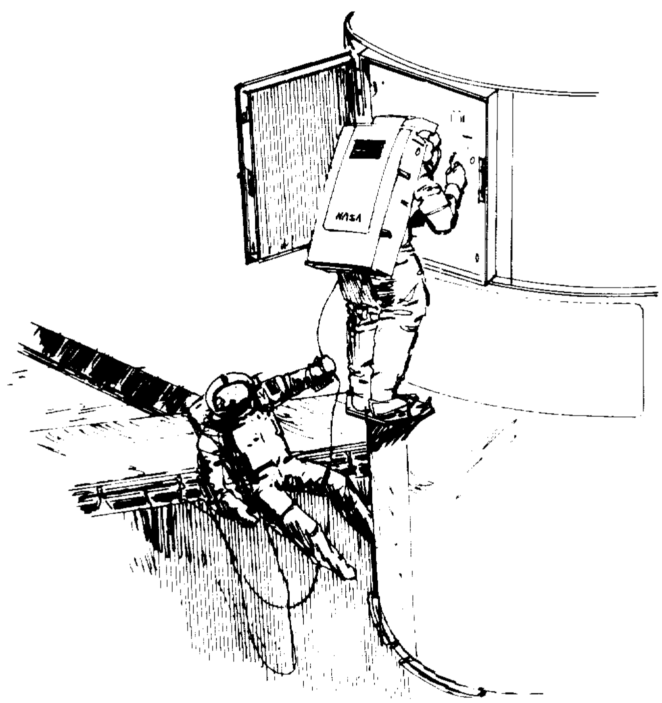


Figure 4–5 Crew EVA by Control Panel

0If temperatures begin dropping, the Orbiter can change orientation to improve the temperature of affected instruments.

If the RMS does not hook onto the SSM grapple by remote control, the crew can make the connection manually. If the RMS fails completely, it may be possible to unlatch the HST and have the crew push the spacecraft out of the Orbiter. Figure 4-6 shows the Orbiter rolling the HST into space.

Should the solar arrays or the high-gain antennas not deploy, the crew can deploy them manually. A crew member would insert a ratchet wrench into a fitting found on the primary and secondary drive mechanisms. The astronaut then could crank each drive by hand until the solar array is erect and the wing is extended. The astronauts also have power wrenches to erect the arrays quickly if needed. Figure 4-7 shows a crew member erecting a solar array mast.

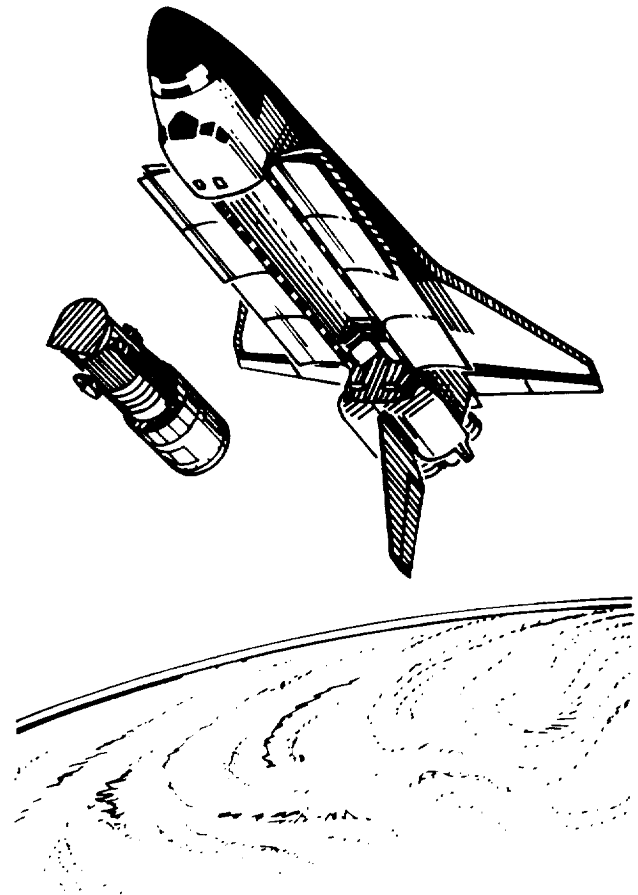


Figure 4–6 Orbiter Rolling the HST Out of Bay

If it appears that the solar array wing may damage the HST or the Orbiter or injure a crew member, the array can be jettisoned. A crew member could remove a clamp ring on the SA drive mechanism on the HST hull and push the array wing away. Figure 4-8 shows a crew member unbolting the solar array before jettisoning it.

NASA has planned a number of workaround maneuvers to prevent any unexpected situations from delaying the release of the Space Telescope.

- If the HST cannot maintain internal temperatures, systems could be affected seriously within the spacecraft. For example, the primary mirror could be permanently damaged if its mounts contract in the cold space environment. If there is no internal power to run

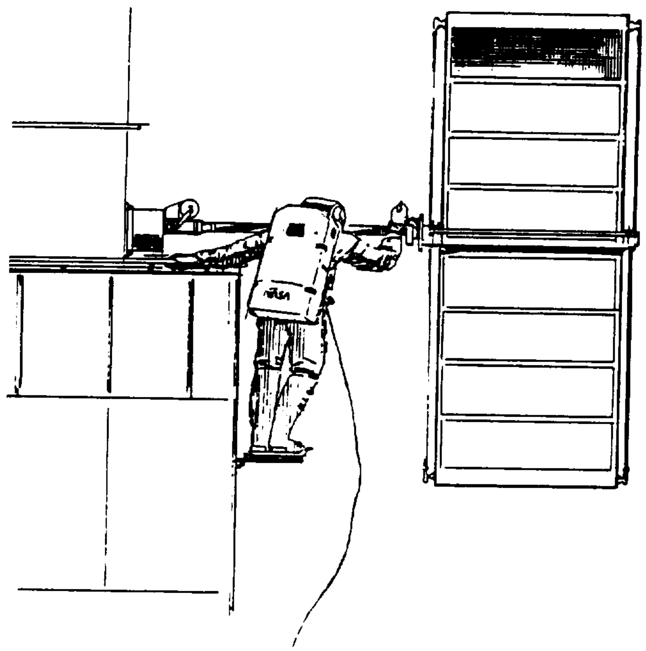


Figure 4–7 Erecting SA Mast

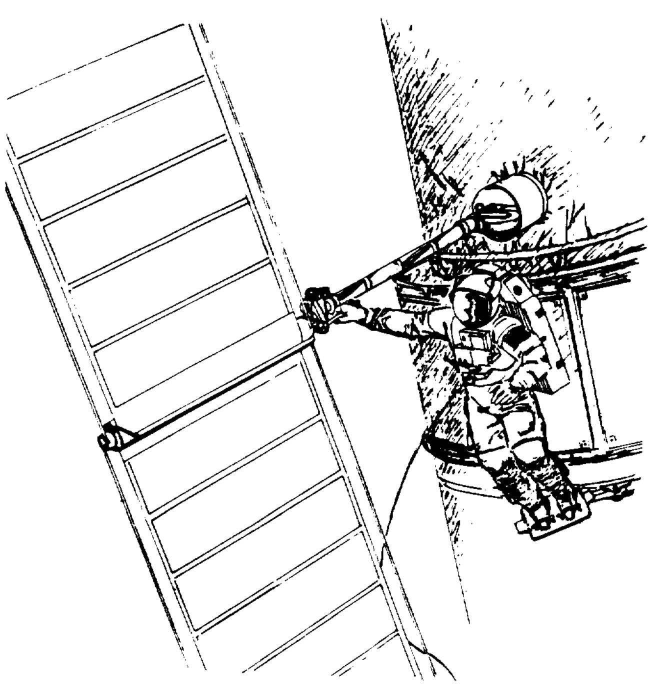


Figure 4–8 Crew Member Unbolting Array

the heaters, the crew immediately will attempt to reconnect the Orbiter umbilical and restore thermal power to the Space Telescope. Then the STOCC would have time to study and correct the internal power problem.

- If the HST cannot successfully deploy at least one SA to begin charging the batteries, the Shuttle must retrieve the spacecraft. Crew members then can extend the SA masts manually or rotate them to face correctly if the masts slew improperly. Crews also can maneuver the HGAs, RMS grapple, and umbilical.

  Before HST redeployment, the crew must reconnect the Orbiter umbilical to recharge the batteries so they do not fail before the SA produces enough power.

- If the batteries discharge past a certain point over a limited time, they cannot recharge and will be useless for power storage. They are vital to the operation of the HST when it is in earth shadow because the SAs cannot produce power.

Failure of any of these workarounds could cancel the mission.

4.1.4.5 Return to Earth. Should it be necessary to return the HST to earth, the following procedure will be performed:

1. Crew members will stow or jettison all appendages, place the HST in the cargo bay using the remote manipulator, and remotely latch down the telescope via the trunnion control panel.
2. The crew will attach the Orbiter umbilical to the HST so external power can replace HST power.
3. The payload interrogator will send STOCC commands to the HST and return status telemetry to the ground.
4. The Orbiter will maintain temperature control within the HST until the telescope is returned to earth.

5. Just prior to re-entry, the cargo bay doors will close to protect the HST, and the STOCC will shut down the HST power and thermal systems.

4.2 MISSION OPERATIONS

Mission Operations covers the testing period of six months, designed to verify that the Space Telescope systems and scientific instruments function, and the science and engineering operational period of the remainder of the mission, at least 15 years.

Once the Hubble Space Telescope enters orbit on its own power, the STOCC will begin orbital verification. This is a thorough check of all systems and scientific instruments. It has two phases: Orbital and Scientific Verification. Orbital Verification (OV) will operate the SSM and OTA subsystems rigorously to stretch the subsystems to Contract End Item (CEI) specification limits. Scientific Verification (SV) similarly will test the scientific instruments, calibrating their systems to meet specifications and checking the test data produced by the instruments. This data will form the early database used by the guaranteed-time observers.

Overall operations will begin as the STOCC approves the HST systems. Science operations will have a high priority, increasing in number as each instrument passes its calibration testing and becomes fully functional. Sharing HST time will be many system operations, such as pointing (slew) maneuvers or on-board engineering calibrations. The planned daily time allotment for Space Telescope activities is charted in Figure 4-9.

The Space Telescope Science Institute (STScI), at John Hopkins University in Baltimore, Md., will schedule and oversee science operations, coordinating the efforts of many international astronomers with different and overlapping goals. The Space Telescope Operations Control Center (STOCC) at Goddard Space Flight Center will run day-to-day system operations that support the science operations. These two organizations comprise the Space Telescope ground system. Lockheed serves as the HST Missions Operations Contractor (MOC) at Goddard, responsible for telescope communications and control.

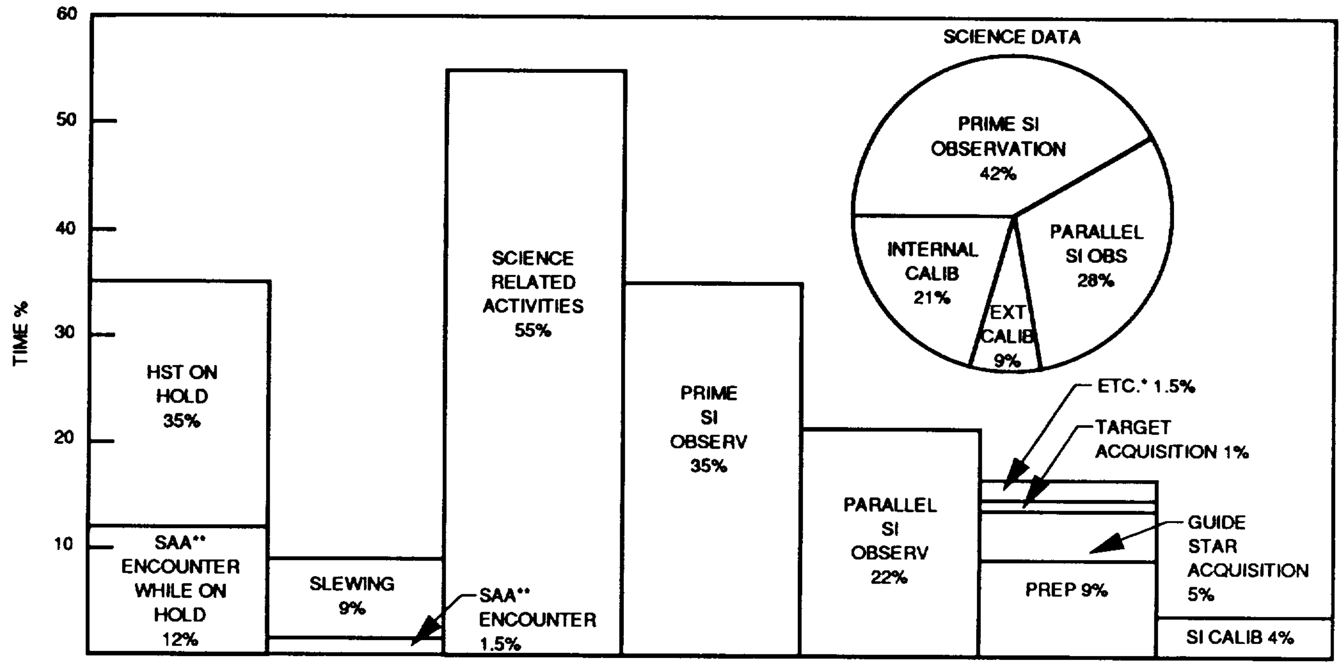
4.2.1 Mission Verification

There are four sequential milestones set for Mission Verification. The first milestone is the testing to be completed before the HST leaves the Orbiter cargo bay. The second milestone will be when the STOCC stabilizes the HST in orbit, ready for Orbital Verification. The third will occur when the telescope passes its system tests and completes Orbital Verification. The fourth milestone will be when the scientific instruments perform tests required to pass Scientific Verification. The first two milestones were discussed in the section on deployment.

4.2.1.1 Orbital Verification (OV). The subsystems that make up the Support Systems Module and Optical Telescope Assembly will face strenuous tests before the STOCC will approve them for science operations. These tests will be interlinked, complex, and subject to change. The following summary focuses on the testing of the pointing control subsystem as an example of the intense verification process the subsystems will undergo.

After the Orbiter releases the HST, the telescope will be in an imprecise orientation. The HST will be under Software Sun Point Control, which means that its attitude places maximum sunlight on the solar arrays for power.

The pointing control subsystem compo-nents will be turned on. The components will be tested to calculate and transmit data to move



NOTES:

* INCLUDES FHST UPDATES. INITIATION OF TRACKING. OTA/SSM CALIBRATION, ETC.

** SSA IS THE SOUTH ATLANTIC ANOMALY WHERE RADIATION BOMBARDMENT IMPINGES ON SCIENTIFIC OBSERVATIONS

Figure 4–9 Time Allocation for HST

the Space Telescope into a better orientation for communications and telemetry.

First the fixed-head star trackers will begin mapping the general location of stars. Meanwhile, the magnetic sensing system will accumulate data on the telescope's orientation relative to the earth's magnetic field. The rate gyro assemblies will assess the Space Telescope pointing attitude (with respect to a stable reference system) and its rate of angular motion as it circles the earth. The coarse sun sensors will keep track of the sun's position.

This data, accumulated over more than 12 hours, will go to ground computers to produce updated position coordinates for the gyros. The HST will adjust its pointing attitude, based on the new coordinates, which in turn means the high-gain antennas then will be able to transmit system status signals to an available Tracking and Data Relay Satellite (see Figure 4-10).

The STOCC then will take the Space Telescope out of Software Sun Point Control and allow the rate gyro assemblies to control the HST pointing (orientation) in orbit.

The NSSC-I computer will be turned on so that the instruments can begin verification tests. Over the next day the rate gyro alignments will be sharpened to improve telemetry and prepare for the operation of the fine guidance sensors (FGSs). On the third flight day, after the STOCC checks out the door's bright-object

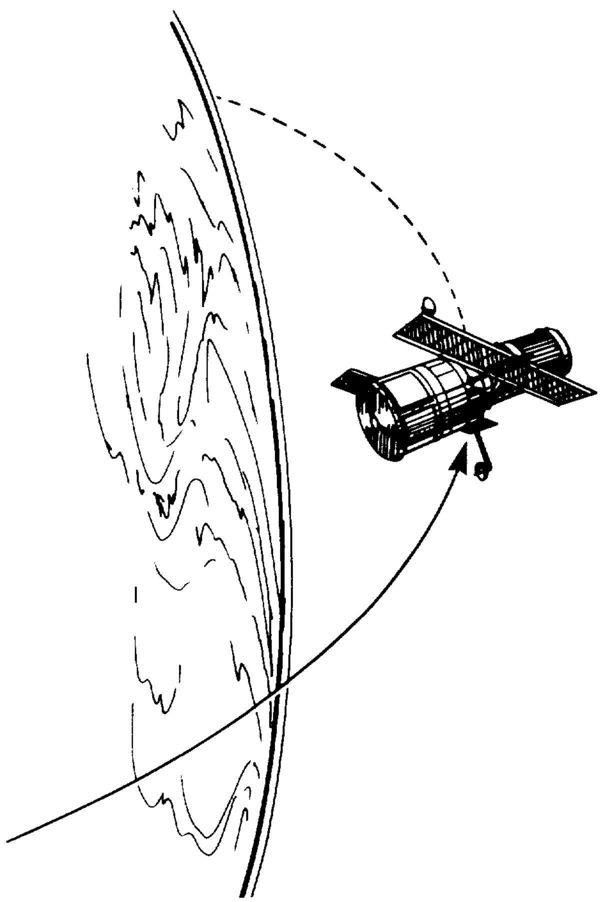


Figure 4–10 HST Adjusts Its Orientation

detection system, the aperture door will open. The Space Telescope now will be ready to test the FGSs, the key to placing star images in the scientific instrument apertures.

The first FGS will be turned on at the beginning of the fourth flight day. At this point the Orbiter will complete its standby mission and can assume other duties. The next three days will be devoted to testing the HST FGS coarse tracking and mapping calibrations. Toward the end of this phase, the STOCC will practice adjusting the secondary mirror actuators in the Optical Telescope assembly to remove distortion. Refinement of the optical path adjustment system will continue into the eleventh day, as will tests to assure that the guidance sensors can align with respect to the Space Telescope axes and each other.

Because each orbit will plunge the telescope from the heat of solar exposure into the cold of earth shadow, the STOCC will test the operational and pointing systems during "hot" and "cold" orbital periods. These tests will tell what effect temperature variations have on the quality of the light reflected through the optical system. The STOCC will use this information to adjust focal positions accordingly by moving the mirror actuators and retesting. The STOCC will continue this retesting process for the entire pointing control subsystem until the system meets its performance specification.

The full range of Orbital Verification is subject to change as circumstances warrant, but OV will follow this general type of testing and retesting.

4.2.1.2 Scientific Verification. The scientific instruments all will undergo similar testing and calibration, once the pointing control subsystem passes its verification tests. In fact, some instruments will test the pointing system capabilities as part of an intertwined series of tests. Generally, however, Scientific Verification will begin after Orbital Verification is completed.

The STScI will be responsible to Goddard Space Flight Center for the successful performance of the scientific instruments. The SV manager at Goddard will run the verification with a specific set of objectives to:

- Demonstrate that the HST, scientific instruments, and guidance sensors are capable of effective scientific work.
- Decide how science and system performances fail requirements and plan workarounds.
- Develop calibration standards against which the scientific instruments and other measuring equipment can compare data for accuracy.
- Fulfill the first two months of scientific observations by the guaranteed-time observers. If the system needs additional time for

verification, the guaranteed- observer time probably will be extended.

Astronomical calibration standards will be used to measure ultraviolet and visual light. For example, astronomers will point the HST at nearby celestial objects with known calibrations and compare these against readouts by the instrument detectors.

In addition to the above goals, the STScI will develop improved operating procedures. It also will gather information for maintenance plans and to select the second set of scientific instruments.

Each scientific instrument must be tuned to its most efficient level through a process much like the pointing system fine-tuning described above. Most scientific instruments have multiple functions, either through use of different filters or focal/optics paths or both. The testing of each instrument will exercise as many combinations as possible. The instruments often will share or overlap observations, so they will also share verification tests.

As with Orbital Verification, possible schedule changes prevent publication of a complete list of scientific verification tests. However, the following test captures the flavor of the verification process.

Each scientific instrument has filter wheels or calibration lamps that could interfere with the image being recorded by another instrument. There are two possible types of interference to test for — direct, from stray lamplight reaching the detectors; indirect, from motion (jitter) of the target beam as wheels rotate. Instruments will be tested in tandem; e.g., the FOC and HSP together.

Many of the science tests will study specific targets, mixed in with guaranteed-time science observations. Since the two cameras will be calibrated more quickly than the complex spectrographs and photometer, NASA expects much more early data from the camers. The apertures for the two spectrographs and the photometer are smaller than the camera apertures, so it is expected to take longer to place the image onto the small apertures and calibrate these instruments. After the five-month period of Scientific Verification — and probably before — all five instruments and the guidance sensors will be ready to play major roles in observations.

4.2.2 Operations

The Mission Operations fulfill the mission of the Space Telescope program in two types of operations:

1. Science operations, which will observe celestial objects and gather data.
2. On-going engineering operations, which will calibrate, test, and maintain the HST's overall performance.

The science and engineering operations often coincide and interact. For example, a scientific instrument may observe a star and calibrate incoming wavelengths against wavelength standards developed during Scientific Verification.

Mission operations are carried out by the Space Telescope ground system, which consists of the Science Institute and Space Telescope Operations Control Center. The STScI oversees science operations. The Institute hosts astronomers, evaluates and chooses observation programs, schedules the selected observations, and stores and analyzes data received from the HST. The STOCC makes all the day-to-day operational decisions, through the Payload Operations Control Center at Goddard Space Flight Center. The STOCC interacts with the STScI, through the Institute-staffed Science Support Center, to make daily science schedules, to process quick-look data and displays, and to manage the science data. Figure 4-11 details the ground functions.

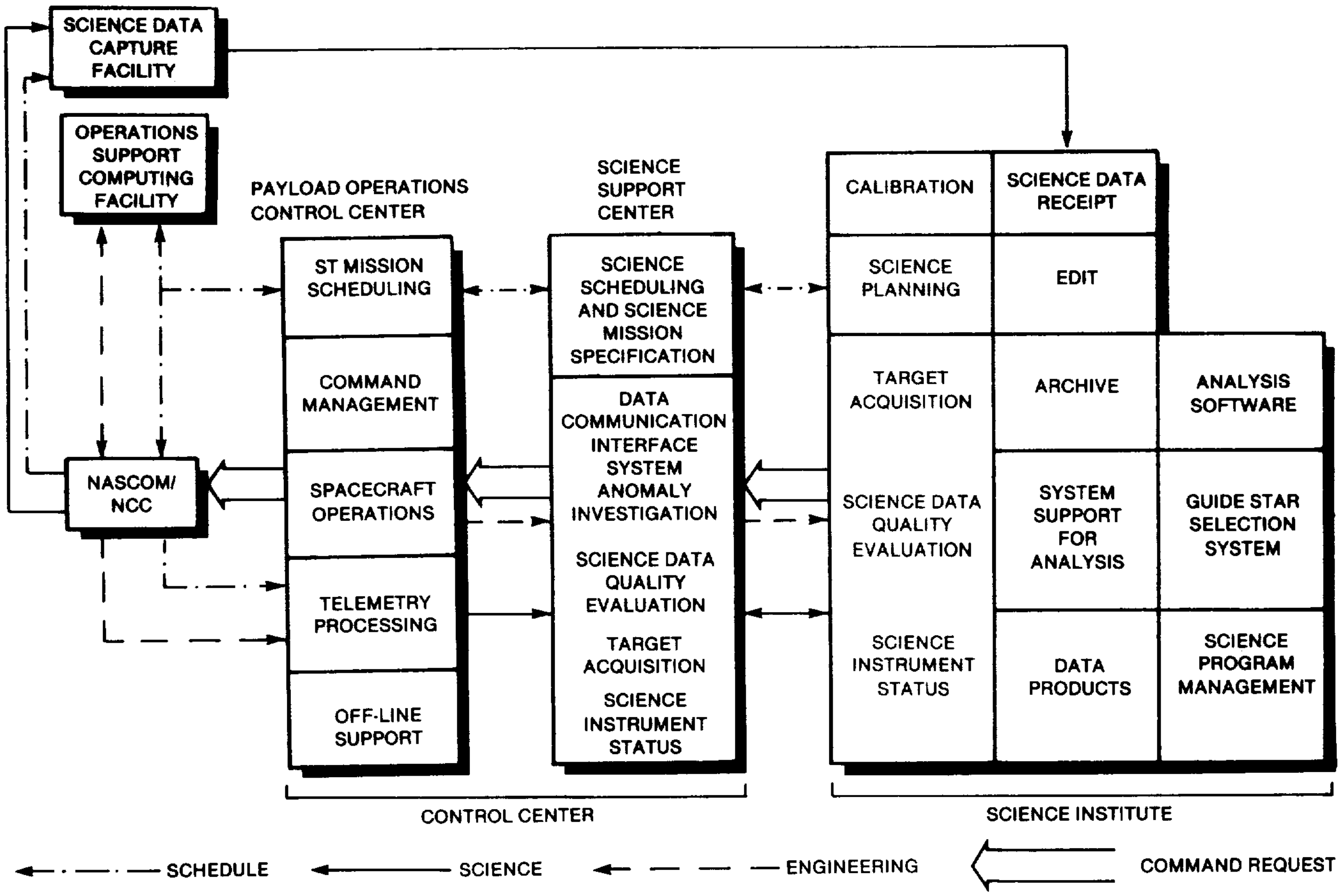


Figure 4–11 Space Telescope Ground System

4.2.2.1 Space Telescope Science Institute. The Space Telescope Science Institute is responsible to Goddard for the science programs on the Hubble Space Telescope. It is operated by the Association of Universities for Research in Astronomy (AURA), a consortium of 20 United States universities that operates several national facilities for astronomy.

The Institute will solicit and review all observation proposals and select observations to be carried out. The STScI will plan and schedule the observations and assist guest observers in conducting observations. The STScI provides the facilities and software to reduce, analyze, archive, and distribute HST data.

It will also monitor the Space Telescope and scientific instruments for any characteristics that could affect the collection of science data. Examples would be instrument performance quality, pointing inaccuracies, and telescope focus.

Scientific Goals. The STScI will help conduct the science program to meet the overall scientific goals of the HST program, set by the STScI and NASA in consultation with AURA's Space Telescope Institute Council and committees representing the international astronomical community.

Some of the scientific goals for the Hubble telescope are:

- Calibrating distances to astronomical objects using improved parallax measurements and a series of distance "standard candles."
- Determining at what rate the expansion of the universe is slowing.
- Gathering information about star formation in galaxies.
- Making photographic and spectroscopic observations of embryonic stars (protostars).
- Finding planetary companions of nearby stars, through imaging or astrometry.
- Resolving dense star-cluster nuclei in search of massive black holes.
- Discovering the composition, temperature, density, and structure of gas in galactic halos, high-velocity clouds, and the interstellar medium.

Institute Software. Computer hardware and software play an important role in the Institute's work. The Science Operations Ground System (SOGS) is a data- management and scheduling computer system, developed by TRW under contract to NASA. The Guide Star Selection System (GSSS) created the Guide Star catalog used by the pointing control subsystem. The Science Data Analysis Software (SDAS) will provide analytical tools for astronomers studying the processed data. The STScI developed the GSSS and SDAS.

SOGS, designed to use six VAX 11/780 computers, handles science planning and scheduling, observation support, software support, and routine data processing. Together these programs will perform the computations needed to run the science operations on the Space Telescope.

The Guide Star Selection System (GSSS) will provide reference stars and other bright objects so the fine guidance sensors can point the telescope accurately. The GSSS will select guide stars that can be located unambiguously in the sky when the sensors point the telescope. The GSSS star catalog has information on 20 million celestial objects, created from 1477 photographic survey plates covering the entire sky.

Figure 4-12 is a photograph of a portion of the catalog. It shows a spiral galaxy, M51, and surrounding stars in that sky sector.

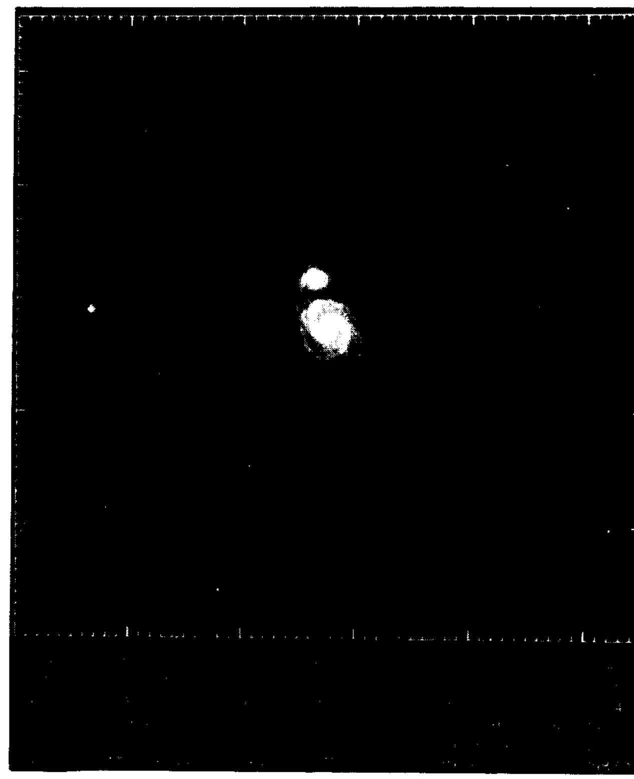


Figure 4–12 A Portion of the GSSS Star Catalog

After SOGS collects, edits, measures, and archives science data, observers will be able to use SDAS application programs to analyze, and interpret their data.

Selecting Observation Proposals. The Institute will select observations by evaluating requests for technical feasibility, conducting peer reviews, and choosing the highest-ranked proposals. Since individual astronomers and astronomy teams are expected to submit many more proposals than can possibly be accepted, a team approach is being encouraged. The final decision rests with the Institute director, advised by a committee of astronomers and other scientists.

The first priority for observations goes to the principal investigators, those scientists and astronomers who designed the instruments. The principal investigators and their contributions are:

- R. C. Bless, University of Wisconsin (High Speed Photometer).
- J. C. Brandt, University of Colorado, formerly with GFSC (Goddard High Resolution Spectrograph).
- R. J. Harms, ARC (Faint Object Spectrograph).
- F. Macchetto, European Space Agency/ STSCI (Faint Object Camera).
- J. A. Westphal, Cal Tech (Wide Field/Planetary Camera).

The principal investigators and other guaranteed-time observers are guaranteed 100% of the observing time for the first three to seven months after overall verification, then 34% between months 8 and 19, 24% for the next 12 months, and 12% for another 10 months. Of the rest of the observing time, the director will reserve 10% for special observations, such as unexpected celestial events (targets of opportunity).

Scheduling Selected Observations. The primary scheduling consideration will be the availability of a target, limited by environmental and stray-light constraints. An example would be a faint object that must be observed when the HST is in the earth's shadow. The schedule will take into consideration system limits, observations that use more than one instrument, and required time for special observations.

Data Analysis and Storage. The STScI will retain data in its archives after analyzing it. Computer resources will include the SDAS and other computer facilities to be selected.

SOGS data-processing will receive science data from the Data Capture Facility, then automatically format and verify the quality of the data. It will calibrate the data to remove instrument interference, such as variation in the detector's sensitivity across the data field. Then the software will place the data on archive computer tapes, from which the data can be formatted into printed reports, printer plots, and photographic prints and negatives. The Institute plans to process all data within 24 hours after it is received.

The SDAS package is written so observers can interact to process images received by the SOGS software and transferred to SDAS. In addition, individual observers will be encouraged to bring their own data-analysis software and reference data.

The Institute will be responsible for storing the massive data expected from the HST. A database management system will record the location and status of data as it pours into the storage banks. Observers and visiting astronomers will be able to retrieve the stored data easily for examination or use in data-manipulation procedures that can be created on the Institute computers.

In addition to the science data, the computers will store engineering data. This can be important for adjusting Space Telescope operations based on engineering findings — for example, that an instrument provides unreliable data in certain temperature ranges — and to develop more efficient use of the HST systems.

4.2.2.2 Space Telescope Operations Control Center. The STOCC will run day-to-day spacecraft operations through three coordinate parts: the Payload Operations Control Center (POCC), the Science Support Center (SSC), and the Science Data Capture Facility (DCF). In addition, the STOCC works with the NASA

Communications Network (NASCOM) and the Tracking and Data Relay Satellite System (TDRSS).

The POCC will use the mission-control facilities at Goddard. These facilities have been used many times before, including the Einstein and International Ultraviolet Explorer spacecraft missions in the 1970's.

The POCC will have five major operational responsibilities: mission scheduling (with the Institute), command management, spacecraft operations, telemetry processing, and off-line support. Mission scheduling will confirm that the science and engineering schedules agree. The POCC will work with the SSC, which is operated by the Institute and represents the astronomer's concerns, to balance the schedule.

For example, if an observation is scheduled at the same time as a required computer update takes place, the POCC and SSC will work out a compromise.

Some commands may pass to the Space Telescope from the POCC, based on specific observation objectives. The POCC will translate those goals into commands, then pass them along to the telescope through the communication network. The commands may re-orient the HST position, open an instrument aperture, turn on the instrument's detectors, request a certain filter or grating setting, or monitor data going from the detector to the instruments transmission device and out through the SI C&DH.

Most specific spacecraft operations will be commanded by software embedded in the HST's on-board computer. In that case, the POCC will order the computer to activate the stored commands.

Telemetry will come into the POCC from the communication satellites and provide information that reflects the status of equipment or the operation of the spacecraft. For example, telemetry can indicate that the voltage going to the rate gyro assembly indicates a power surge, which could disable a rate gyro assembly and affect the stability of the HST. The POCC will take steps to defuse the voltage surge or switch to a backup gyro until the problem can be solved. In many cases, telemetry data will involve the consultation of the SSC and the STScI, particularly if it affects an on-going observation. An example would be data that require repointing the HST.

Off-line support means that the POCC will provide background support for other organizations that have direct responsibility for a task. An example would be supporting NASCOM, even though the POCC is not directly responsible.

The Science Support Center will coordinate science objectives with the STScI, acting as a conduit between the STOCC and the Institute. The daily science schedule will pass through the SSC, and the STOCC will match the information with the engineering and calibration needs of the telescope components. If, for example, a science schedule requires the use of a spectrograph, the STOCC may want to avoid calibrations of the filter wheels in the Faint Object Camera so jitter would not affect the spectrographic operation. SOGS would resolve this conflict.

One important function of the SSC will be to support observers requiring a "quick-look" analysis of data being gathered. The SSC will alert the POCC to that need, and the incoming data can be processed for the observer. For example, the observer can look at preliminary measurements coming from the photometer to see when to place the beam into a different aperture.

The third important part of the STOCC is the Data Capture Facility. This is where the data will arrive from NASCOM for science handling. The facility will reformat data from the transmission format, check for any noise or transmission problems, and pass each packet of data along with a data quality report.

Support for the STOCC will come from the Spaceflight Tracking and Data Relay Network (STDRN), composed of the Tracking and Relay Satellite System (TDRSS), the NASA Communications Network (NASCOM), and the Ground Spaceflight Tracking and Data Network (GSTDN).

The TDRSS will have two communications relay satellites placed 130 degrees apart, with a ground terminal at White Sands, New Mexico. There will be a small "zone of exclusion" where the earth blocks the telescope signal to either of the satellites, but up to 91% of the HST's orbit will be within communication coverage. The TDRSS satellites receive and send both single-access (science data) and multiple-access (commands and engineering data) channels.

The NASCOM system leases domestic satellites for commercial communications purposes, such as television transmission. These satellites will pass along data from the TDRSS directly to the STOCC.

The GSTDN, with eight stations world-wide, provides ground communications to supplement the TDRSS. Unfortunately, the available communication time is too limited for lengthy data transmission.

4.2.3 Operational Characteristics

Three major factors affecting the success of the Space Telescope will be the orbital characteristics for the spacecraft, its maneuvering characteristics, and the communications characteristics for sending and receiving data and commands. These are discussed below.

4.2.3.1 Orbital Characteristics. The orbit of the Hubble Space Telescope will be approximately 330 nmi (607 km). The spacecraft will maintain an orbit between a minimum operating altitude of approximately 200 nmi (368 km) — to keep above altitudes where atmopheric drag comes into noticeable play — and the deployment orbit. The orbit will incline at a 28.5- degree angle from the equator because the Shuttle launch will be due east from Kennedy Space Center. The chosen orbit will put the sun in the HST orbital plane so that its light falls more directly on the solar arrays. In addition, the orbit will be high enough that aerodynamic drag from the faint atmosphere at that level will not decay the telescope's orbit to below the minimum operating altitude.

The Space Telescope will complete one orbit every 97 minutes. During each orbit the telescope will pass into the shadow of the earth. The time in shadow varies from a maximum of 36 minutes to a minimum of 28 minutes. The variation during a "nominal" 30-day period is between 34.5 and 36 minutes in shadow. If, when viewing an object, the earth itself blocks the object from the telescope, the HST will have to re-acquire the object as the spacecraft comes out of earth shadow. Faint-object viewing will be best when the HST is in the earth shadow. Figure 4-13 shows the nominal orbit.

The Space Telescope orbit will be tracked by the TDRSS, which will plot the spacecraft's orbit at least eight times daily and send the data to the Flight Dynamics Facility at Goddard. This will help predict future orbits, though some inaccuracy in predicting orbital events such as exit from earth shadow is expected and unavoidable.

The environmental elements with greatest impact on the HST orbit will be solar storms and other solar activities. These "thicken" the upper atmosphere and increase the drag force on the telescope, thus accelerating the orbit

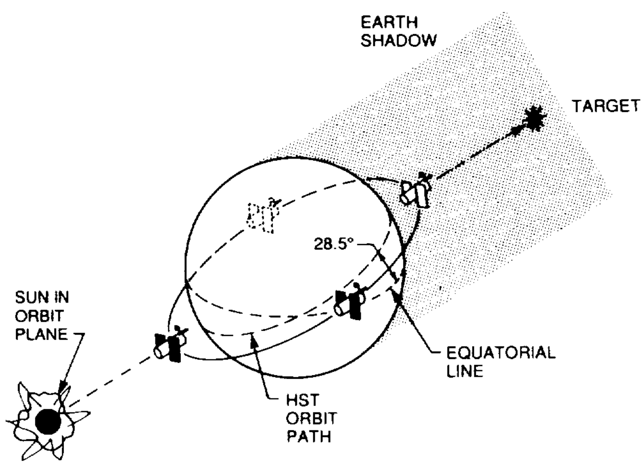


Figure 4–13 HST Nominal Orbit

decay rate considerably. The Space Telescope will be launched into a peak of high solar activity. This could affect the launch and orbit altitudes required by the Space Telescope to complete the first five years of the mission without falling below the 247-mi limit. If "worst-case" studies hold, the Space Shuttle may need to reboost the HST into a higher orbit earlier in the mission than expected.

Celestial Viewing. The telescope will be pointed toward celestial targets as a normal orientation to expose instrument detectors for up to 10 hours, if needed. A "continuous viewing" zone will exist, parallel to the orbit plane of the HST and up to 18 degrees on either side of the north and south "poles" of that orbital plane (see Figure 4-14). Otherwise, celestial viewing depends upon how long a target remains unblocked by the earth.

Another factor affecting the observation of celestial targets will be the amount of shadow time available for faint-object study. Shadow time for an observation varies with the time of year and the location of the target, relative to the HST orbit plane. Astronomers will use a geometric formula to decide when in a given period a target will be most visible while the HST is in shadow.

Other sources affecting celestial viewing will be zodiacal light and integrated or background starlight. These will affect the viewing with certain instruments, such as the light-intensity sensitive High Speed Photometer.

Solar-System Object Viewing. Solar System objects also will be affected by the factors mentioned for celestial viewing. In addition, the Space Telescope also must work with imprecise orbit parameters for itself and objects such as the outer planets and comets. For example, the position of Neptune's center may be off by 21 km when the sensors try to lock onto it. The reason is because the HST is changing its position in orbit, which affects the pointing direction toward nearby objects. However, most Solar System objects are so bright that the telescope will need only a quick "snapshot" of the object to fix its position. Tracking inaccuracies are more likely to cause a blurred image if they occur with long-exposure observations of dim targets.

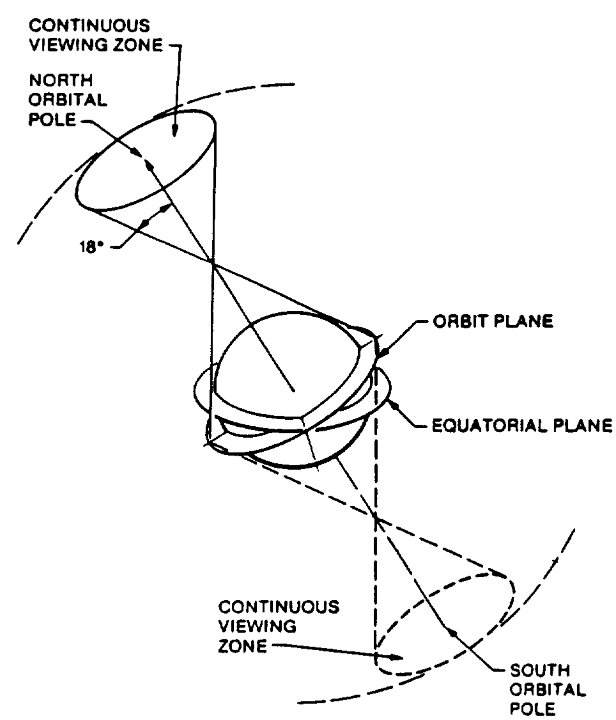


Figure 4–14 "Continuous-Zone" Celestial Viewing

The Space Telescope's attitude roll may also affect the view of the object and require a maneuver that rolls the spacecraft more than the 30-degree limit (for example, to place the image into a spectrographic slit aperture).

Tracking interior planets (Mercury and Venus) with the HST will place the sun within the telescope opening's 50-degree sun-exclusion zone. To minimize the danger from this exposure, the telescope will view these objects using the earth to block (occult) the sun; i.e., after the sunset shadow falls on the HST. See Figure 4-15 for a rendering of how the HST would observe Venus.

Lunar Occultation Viewing. The fine guidance sensors will "look away" when the HST approaches within ten degrees of the bright moon. But, by overriding the controls that protect the sensor star selector servos, the ground control team could use the moon as an occulting object for an observation. The moon likely would be between its "new-moon" and "quarter-moon" phase so the occulting edge, which is in shadow, precedes the illuminated part of the moon (see Figure 4-16).

Natural Radiation. Energetic particles from different sources will bombard the HST continuously as it travels around the earth. Geomagnetic shielding will block much of the solar and galactic component of particle "radiation."

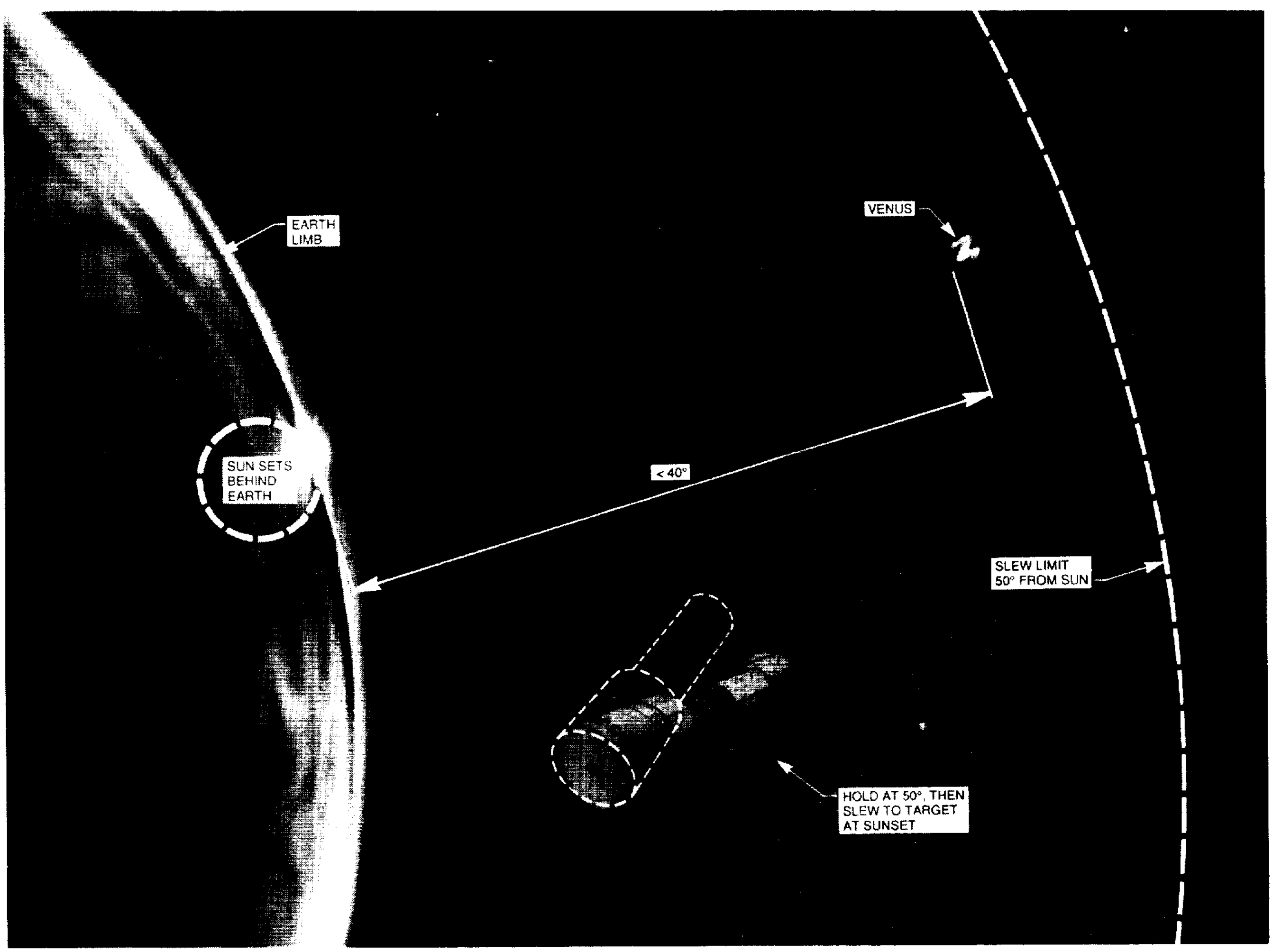


Figure 4–15 Observing Venus

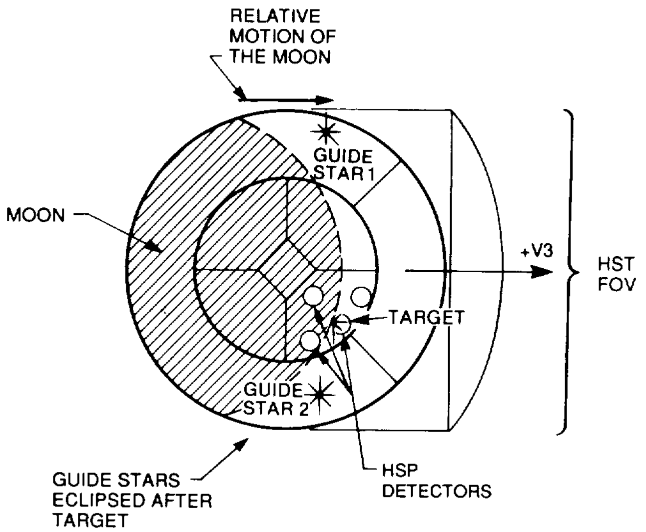


Figure 4–16 Using the Moon as an Occulting Disk

When the Space Telescope passes through the South Atlantic Anomaly (SAA), a "hole" in the earth's magnetic field, charged particles could enter the telescope and strike the instruments' detectors, emitting electrons and producing false data.

During verification, the Institute will run tests to measure the effect of particle radiation on instrument data. If it appears that the effects are significant, the photon-counting devices in the cameras probably will not be used when the spacecraft passes through the SAA. The noise produced by this bombardment also could affect the ability to lock onto guide stars. Nonetheless, the spectrographs and photometers may be usable if the guidance sensors can hold guide stars or the rate gyros can produce a precise image.

The Space Telescope will pass through the SAA for segments of eight or nine consecutive orbits, then have no contact with it for six or seven orbits. Each encounter will last up to 25 minutes. In addition, the SAA rotates with the earth, so it occasionally will coincide with the HST as the spacecraft enters earth-shadow observation periods. Careful scheduling will minimize the effect of the SAA on the mission, but it will have some regular impact.

Solar flares are strong pulses of solar radiation, accompanied by bursts of energetic particles. The earth's magnetic field shields the lower magnetic latitude regions, such as the HST orbit inclination, from most of these charged particles. The flares are monitored regularly by NASA, and the HST could stop an observation until the flares subsided. The greatest physical danger would be crew extravehicular activity, which would be halted until the flares subsided.

4.2.3.2 Maneuver Characteristics. The Space Telescope will change its orientation in space by rotating its reaction wheels, then slowing them; the momentum change caused by the reaction will move the spacecraft. It will be able to move at a baseline rate of 0.22 degrees/sec or 90 degrees in 14 minutes. Figure 4-17 illustrates a roll and pitch maneuver.

When the HST maneuvers, it will take a few minutes to track and lock onto a new target and will accumulate drift errors. This means a larger region of the sky must be scanned for guide stars.

One consideration with maneuvering will be the danger of moving the solar array wings out of the sun's direct radiation for too long. In addition, there is some concern that unprotected portions of the SSM aft shroud could be affected thermally. Therefore, there are limits to maneuvers beyond a certain range in angle and time.

When the HST performs a pitch to a target near the 50 degree sun-avoidance zone, the telescope will curve away from the sun. For example, if two targets are opposed at 180 degrees just outside the 50-degree zone, the HST will follow an imaginary circle of 50 degrees around

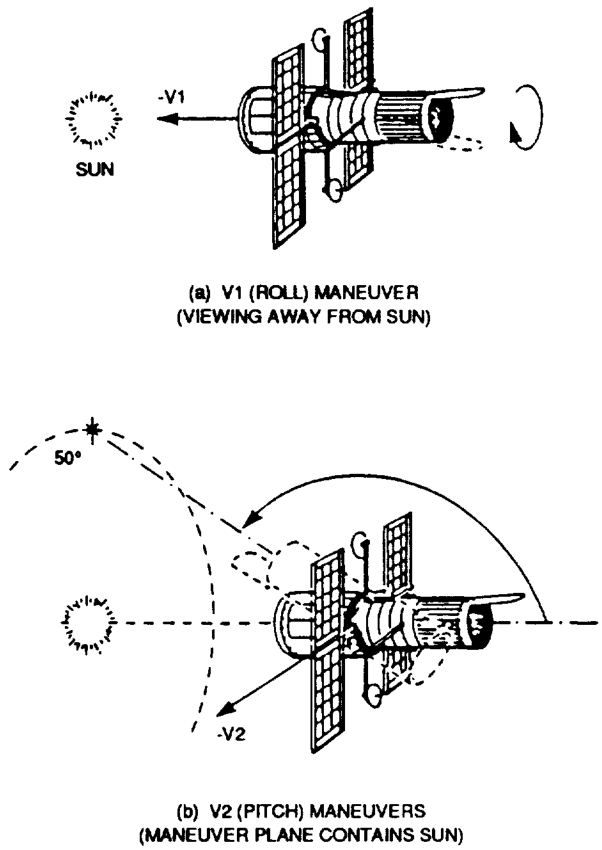


Figure 4–17 HST Single-Axis Maneuvers

the sun until it locates the second target (see Figure 4-18).

4.2.3.3 Communication Characteristics. The HST will communicate with the ground via the Tracking and Data Relay Satellite System (TDRSS). With two satellites placed 130 degrees apart in longitude, the maximum amount of contact time will be up to 94.5 minutes of continuous communication, with only from 2.5 to seven minutes in a "zone of exclusion," out of reach of either TDRS (see Figure 4-19).

However, orbital variations by the HST and communications satellites will affect this ideal situation to widen the zone of exclusion slightly.

The Goddard Space Flight Center Network Control Center will schedule all TDRSS communication. The Space Telescope will have a general orbital communication schedule, supplemented by specific science requests. The Network Control Center will prepare advance schedules 15 days before the beginning of each mission week. Most HST requests are expected to be filled with no conflicting TDRSS requests

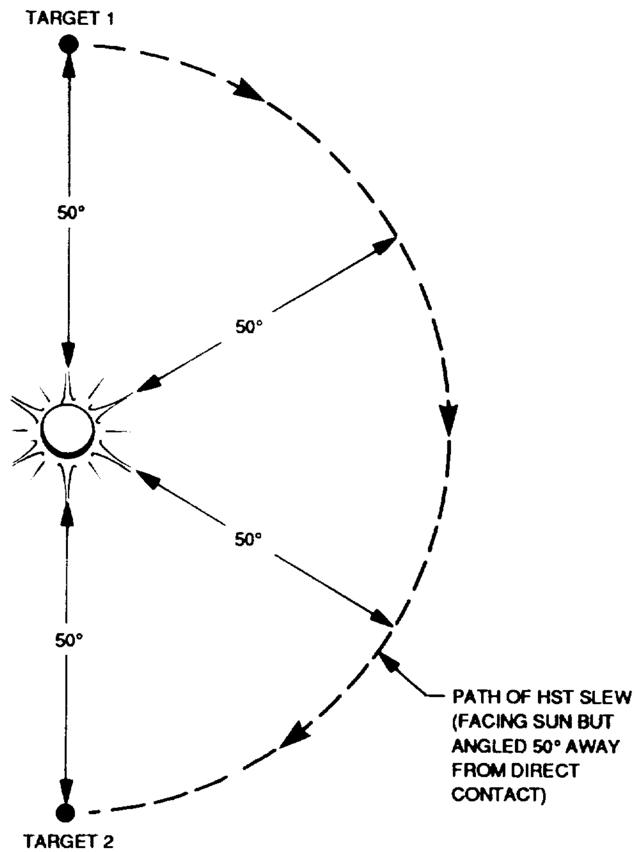


Figure 4–18 Sun-Avoidance Maneuver

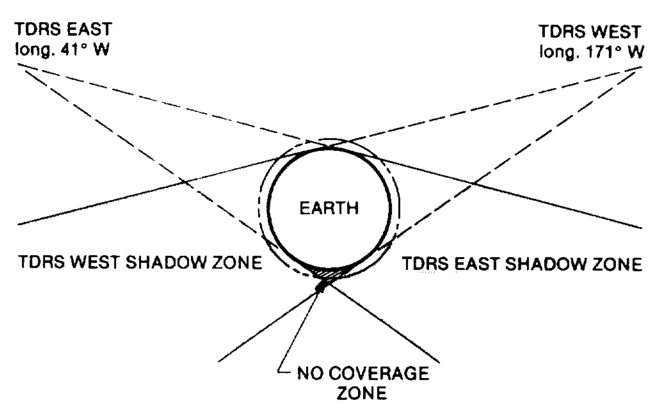


Figure 4–19 TDRS-HST Contact Zones

from other spacecraft, at least in the early part of the mission.

The backup communication link will be the Ground Spacecraft Tracking and Data Network (GSTDN). The GSTDN will receive engineering data, or science data if the high-gain antennas cannot transmit to TDRSS. The longest single contact time will be eight minutes.

The limiting factor of this backup system will be the large gap in time existing between contacts with the HST.

In practical terms, at least three GSTDN contacts would be required to read data from a filled science tape recorder — with gaps of up to 11 hours between transmissions.

Each high-gain antenna will maintain continuous contact with one TDRS to avoid unnecessary gaps in communication. Each antenna can track the communication satellite, even during fine-pointing maneuvers.

The low-gain antennas will provide at least 95% orbital coverage via TDRSS for the minimum multiple-access command rate used.

4.3 MAINTENANCE

Another phase of the Space Telescope mission operations is maintenance in orbit. The HST is the first spacecraft designed for maintenance while in orbit. Maintenance missions (MMs), scheduled approximately every five years, would occur for several reasons:

1. Normal degradation of equipment — Some equipment will need to be replaced after the HST has been in orbit for several years such as the nickel-hydrogen batteries, with a five-year lifespan.
2. Random equipment failure — if a unit's loss endangers continuation of the mission, such as loss of power or communication capabilities, an unscheduled maintenance mission may be necessary to replace the equipment. The Space Telescope has been designed with redundant capabilities, so most systems can function even if the main unit in that system is impaired.
3. Technology advances providing upgraded equipment advances in technology may justify replacing operating equipment. For example, NASA currently is developing second-generation scientific instruments to extend the science mission objectives.

The decision-making and operational responsibility for HST maintenance, when that is required, currently lies with Marshall Space Flight Center (MSFC). Eventually Goddard Space Flight Center (GSFC) will assume that responsibility. Figure 4-20 shows the process involved in deciding whether or not to schedule a mission.

During a maintenance mission, the Space Shuttle will rendezvous with and recapture the Space Telescope. Then, the crew will perform their maintenance assignments while the HST is berthed in the Orbiter payload bay. A mission currently would be scheduled for seven days, with the extra-vehicular activity (EVA) scheduled for Flight Days 3 and 5. The generic MM timeline is in Figure 4-21.

The Space Shuttle will carry up to two Orbital Replaceable Unit Carriers (ORUC) packages with replacement units that would be exchanged (called changeout) with the existing units during the EVA period.

The following typical example outlines the procedures for replacement of a selected ORU during a maintenance mission.

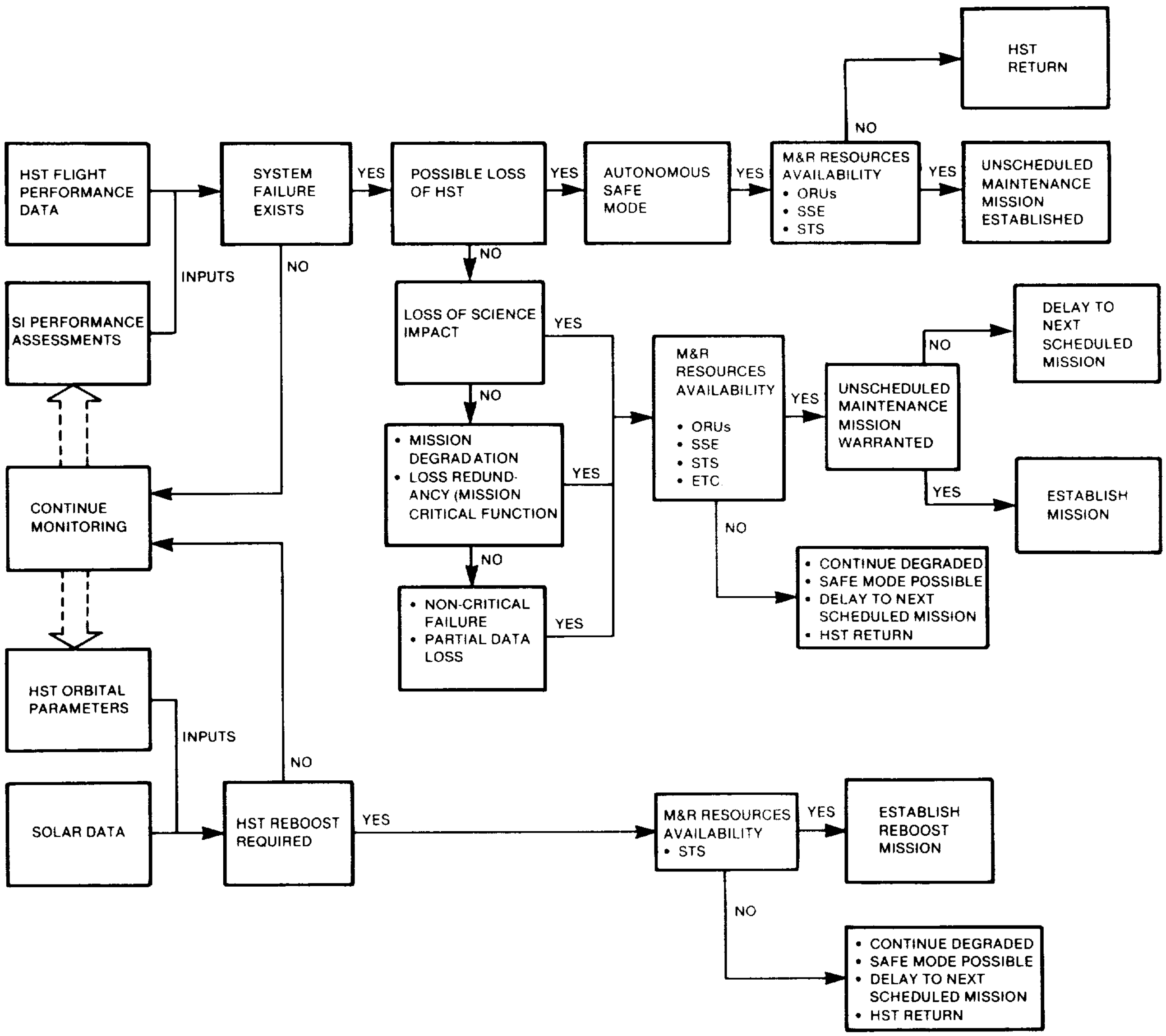


Figure 4–20 MM Call-Up Trip Decision Process

4.3.1 Maintenance Scenario

The Shuttle will launch and rendezvous with the Space Telescope on the second flight day, and retrieve it as follows:

1. The STOCC will report the HST attitude, stability, and whether the arrays and high-gain antennas are extended or retracted.
2. The STOCC will command the Space Telescope to stow the antennas and solar arrays and close the aperture door.
3. The Orbiter will match the telescope orbit, minimizing contamination of the HST from thruster propulsions.
4. A crew member will control the remote manipulator system (RMS) arm and grapple onto the HST forward shell.
5. The astronaut maneuvering the HST with the RMS will berth the telescope on the Flight Support Structure (FSS), guided by the camera on the base of the FSS platform.

When the Space Telescope is latched to the FSS, the crew can tilt or rotate the berthed HST (see

CREW ACTIVITY DAYS	
FLIGHT DAY 1	Launch/On-Orbit Preparation
FLIGHT DAY 2	Rendezvous/Retrieval
FLIGHT DAY 3	EVA #1
FLIGHT DAY 4	HST Reboost/Crew Rest
FLIGHT DAY 5	EVA #2
FLIGHT DAY 6	HST Checkout/ Redeployment
FLIGHT DAY 7	De-orbit/Landing

Figure 4–21 Maintenance Mission Timeline

Figure 4-22). During the EVA the HST will be vertical relative to the Orbiter cargo bay. After each EVA the HST is tilted to a 32.5-degree position and latched to the ORU carrier.

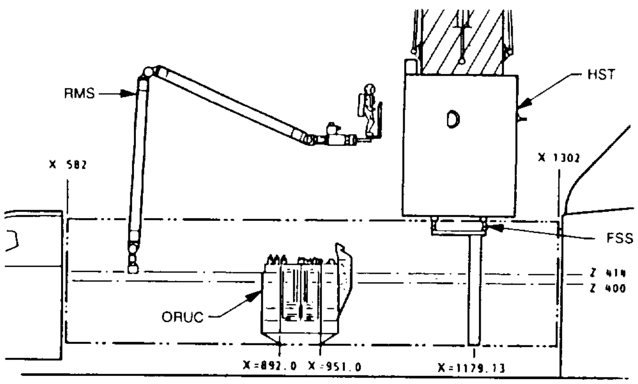


Figure 4–22 HST In Position on FSS

Two crew members, designated EV1 and EV2, will suit up for EVA. EV1 is the crew member who removes and installs ORUs on the HST, working from a portable foot restraint (PFR) that can be placed in receptacles throughout the HST. EV2 is the crew member who, working from the RMS manipulator foot restraint, removes and installs ORUs on the ORUC, passing them to EV1. The EVA crew is limited to six hours of EVA in a 24-hour period.

On Flight Day 3 the EVA crew prepares to pass through the Orbiter airlock, which will take them into the Orbiter cargo bay. They communicate with the crew member maneuvering the RMS arm from inside the Orbiter (called the IV member for intra-vehicular), and with the STOCC through the IV crewmember.

After leaving the airlock, EV1 and EV2 attach their personal safety wrist tethers to a tethering cable that runs along each of the Orbiter cargo bay sills and protects the crew members from floating off once in the cargo bay. EV1 moves to the cargo bay stowage assembly containing EVA equipment to gather a miniworkstation, tethers, two tool caddies, and a PFR. Meanwhile, EV2 unstows the RMS manipulator foot restraint (MFR) and installs it into the RMS grapple fixture, then configures the MFR with tool boards and portable lights and handles. Finally EV2 climbs onto the MFR, attaching one safety tether to a D-ring on the EVA suit left wrist and a second safety tether to the RMS handrail. Now EV2 moves to the ORU carrier in the cargo bay, with the IV crewmember operating the RMS. EV2 moves to the replacement DF-224, mounted on the ORUC, removes the covering thermal blanket, attaches a tether to the replacement DF-224, then releases the six J-hooks holding the computer on the ORUC. EV2, tethered to the DF-224, moves to the Support System Module (SSM) equipment section Bay 1 to assist EV1 in replacing, or changing out, the DF-224 computer.

EV1 inserts the PFR in Receptacle 27, on the guiderail just below the door to Bay 1, then steps into the restraint and locks the suit's boots in place. EV1 releases the six J-hooks holding the door closed, then opens the door. EV1 waits for STOCC approval to disconnect the DF-224, which is communicated through the IV. Then EV1 disconnects seven wing-tab connectors at the side of the DF-224 and the two wing-tab heater connectors. EV1 tethers to the DF-224, releases the six J-hooks to remove the computer, then pulls the computer from its mounting location and transfers the original DF-224 to EV2. EV2 tethers to the original DF-224 and transfers the replacement DF-224 to EV1. Then EV2 takes the original DF-224 to the ORUC and installs it where the replacement unit was stowed. Meanwhile, EV1 has tethered and positioned the replacement DF-224 in Bay 1.

Now EV1 engages and torques tight the six J-hooks, attaches the connectors to the new unit, and informs the IV crewmember that the DF-224 is installed. EV1 closes the Bay 1 door, re-engages the J-hooks and tightens them, stows the tools on suit tethers, exits the PFR, and removes it from Receptacle 27.

This operation takes approximately 55 minutes.

The two days of EV activity follow this general pattern, with the two crew members working together, one removing the units to be replaced, the other retrieving the replacement unit and stowing the removed unit for the return to earth.

The final decision on which units to replace will depend upon the status of the HST flight configuration. For example, the batteries may or may not be replaced, depending upon the degradation of their charging/discharging capacity.

After completion of the two-day maintenance mission, the crew will redeploy the HST, then return to earth with the ORCU and its complement of replaced units.

4.3.2 Reboosting the Space Telescope

If the Space Telescope's orbit has decayed below a minimum acceptable altitude, the Shuttle can reboost the spacecraft to a higher orbit. This is scheduled on the flight day between EVA1 and EVA2.

For this operation, the Space Telescope will be latched to the ORUC keel latch (see Figure 4-23). With the HST latched to the ORUC in

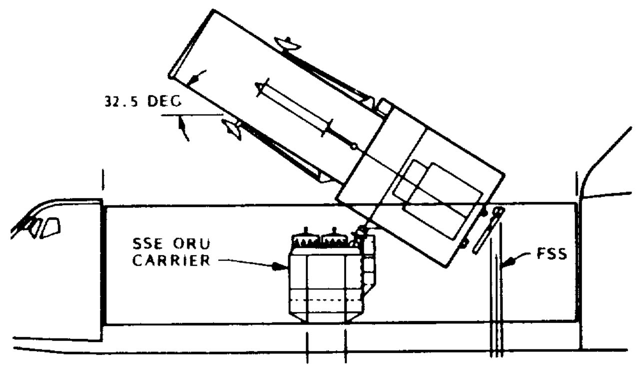


Figure 4-23 HST in Reboost Position

the cargo bay, the Orbiter will move to a higher altitude (see Figure 4-24).

When the Shuttle reaches the new orbit altitude, and upon completion of the planned crew maintenance activities, the crew deploys the Space Telescope in the same manner as the original deployment.

4.4 MISSION OBSERVATIONS

The Hubble Space Telescope will study many specific targets in the sky in its lifetime. Much of the observational work will be highly technical and very specific, such as estimating the ratio of helium to hydrogen in quasi-stellar objects

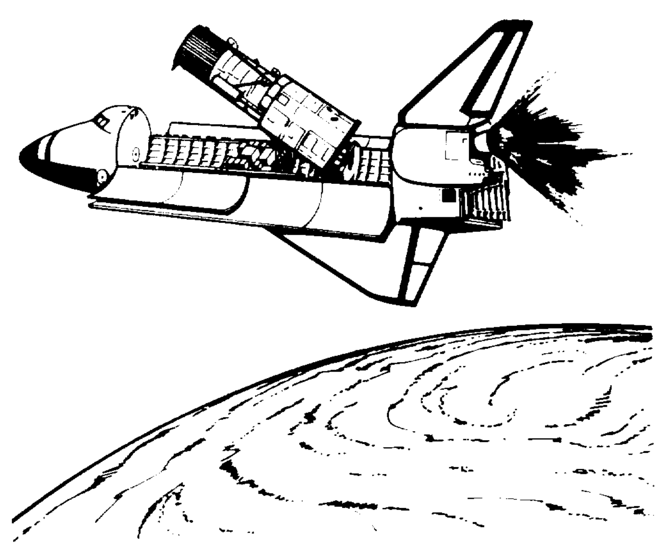


Figure 4-24 Shuttle Reboosting the HST

(quasars) to evaluate the age of the quasar. But general observational goals set for the Space Telescope include:

- Measuring the distance to the objects farthest away from us, and developing better standards to use in measuring the immense distances in space.
- Studying how stars form, by examining the chemical composition of existing stars and of gaseous nebulae, which astronomers feel are the birthplace of stars, and observing the nuclear explosions that signal the beginning of a star's life.
- Searching for information on many mysterious objects in the universe, such as black holes, quasars, pulsars, exploding galaxies, and even the outer planets in our Solar System.
- Examining the most distant objects for clues to the origin and early development of the universe, including the existence of matter before galaxies formed, and invisible matter that astronomers think makes up as much as 90% of the bulk of the universe.

Many of these observations are discussed in Section 3 as they relate to specific scientific instruments. This section will present observation examples to demonstrate the process involved in an observation.

Because there are so many variables in the steps of each individual observation, it is impossible to present an example that represents all observations the Hubble Space Telescope will make. Nonetheless, the following section will approach two "typical" observations.

The two observations selected are the study of the Vela pulsar by the High Speed Photometer, with parallel observation by the Wide Field/ Planetary Camera, and a "target-of-opportunity" study of an exploding supernova by the Goddard High Resolution Spectrograph. Both mission examples are based on studies by the Hubble Space Telescope project team.

4.4.1 Observation Procedure

The major steps required in the observation process are target acquisition and observation, data collection and transmission, and data analysis.

4.4.1.1 Acquisition and Observation. Each scientific instrument has an entrance aperture, all located in different portions of the HST focal plane (see Figure 4-25). The different position of the apertures will make precise pointing a sometimes-lengthy procedure for the fine guidance sensors (FGSs). In addition to the small aperture sizes in which the FGS must center the target, there is the time it will take to reposition the Space Telescope — an estimated 18 minutes to maneuver 90 degrees, plus the time the FGSs take to acquire the guide stars. If the HST overshoots its target, the fixed-head star trackers may have to make coarse-pointing updates before the HST can use the FGS again.

To increase the probability of a successful acquisition, the HST flight software allows the use of multiple guide-star pairs to account for any natural contingencies that might affect a guidestar acquisition — such as a guide star being a binary star and preventing the FGSs from getting a "fine lock" on the target. Therefore, an observer can submit a proposal that includes a multiple selection of guide-star pairs. If one pair proves too difficult to acquire, the sensors can switch to the alternate pair. However, each observation has a limited total time for acquiring and studying the target. If the acquisition process takes too long, the acquisition logic switches to coarse track mode for that observation to acquire the guide stars.

There are three basic modes that will be used to target a star. Mode 1 will point the HST, then transmit a camera image, or spectrographic or

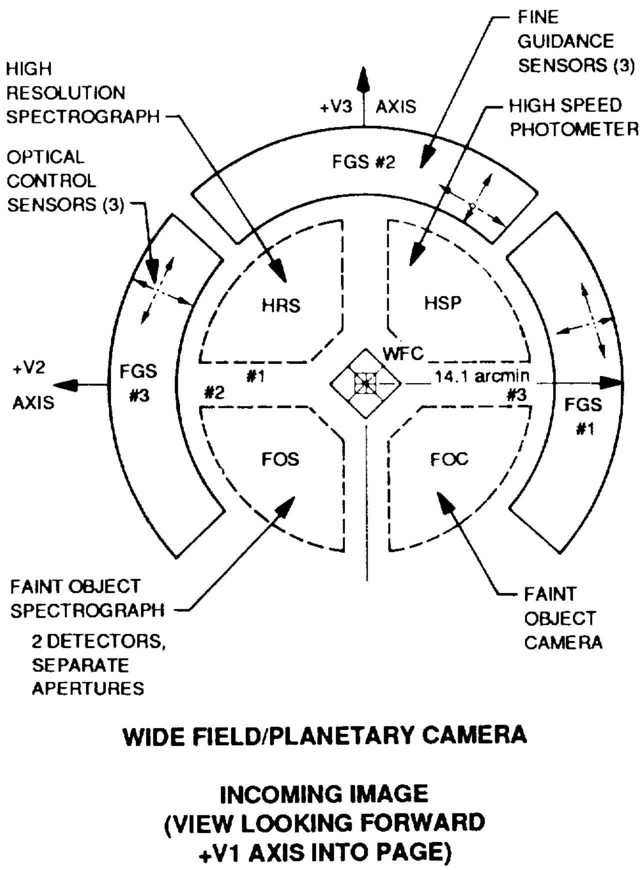


Figure 4–25 HST Instrument Apertures

photometric pseudo-image, to the STOCC. Ground computers can make pointing corrections to precisely point the HST, and the coordinates will be passed up through the DF-224 computer. Mode 2 will use the on-board facilities, processing the information coming from the larger target apertures, then aiming the HST to place the light in the chosen apertures. Mode 3 will use the programmed target coordinates in the Star Catalog or updated acquisition information to re-acquire a previous target. This is called "blind pointing" and probably will be mostly for generalized pointing and for the Wide Field/Planetary Camera, which does not require such precise pointing. Mode 3 likely will rely increasingly on the updated guide-star information from previous acquisition attempts, stored in the computer system.

Section 2.3.1 details how the FGSs operate to lock onto a guide star.

4.4.1.2 Data Analysis. Once observations begin, SOGS will schedule the expected data transmission from the tape recorders, usually within a few hours of collecting the data. Status information will be readied so it can accompany the data. Data will pass from the observing instrument to the SI C&DH, where the science data formatter will convert the data into transmittable packets. From the SI C&DH the data will pass to the high-gain antennas, which will beam the data to the TDRS. The TDRS will pass along the data packets to the White Sands ground terminal, which will transmit the information to NASCOM. The science data will go to the Data Capture Facility (DCF) via a NASCOM satellite, then from the DCF to the STScI for processing (see Figure 4-26). The POCC will receive engineering data when it is transmitted.

If the Space Telescope moves out of communication with the TDRS, the collected data will go onto a Space Telescope science tape recorder for later transmission.

Incoming data will go into SOGS, where the data base management converts the data into SOGS format before storing the updates in the Science Institute archive. The SOGS software will examine the data for duplication and missing or bad portions of data. Bad data can be

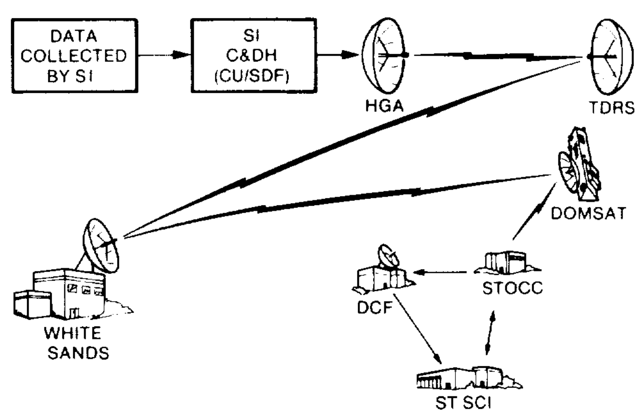


Figure 4–26 Data Transmission Pathway

retransmitted if it is stored on HST tape recorders.

SOGS will edit the usable data; unusable data will go into a separate file for troubleshooting and salvage, if possible. SOGS will edit the data by filling gaps from missing data with blank "fillers." Then it will reformat the data into a format used for all incoming science and engineering data. This will be done so the astronomers can compare the science and engineering data packets to verify the observation. For example, engineering data may indicate that the observing instrument had a malfunction that flooded the data diodes and produced useless data.

A final editing step will calibrate the data. This step will convert telemetered data into scientific form and remove instrument signatures. For example, software will convert spectrograph wavelength measurements from pixels to angstroms and remove noise signals coming from grating carrousel movements. Calibrated data will be checked for any problems that could indicate faulty transmission, software errors, or instrument troubles.

Once calibrated and checked, the data can be stored in the STScI archives for future study or use, or it can be sent to printers, tape drives, film writers, and other output sources.

4.4.2 Observation Examples

There are many observations being planned; below are two examples that point up the type of expected operations involved in the HST's selected observations.

4.4.2.1 Vela Pulsar Observation. The Vela pulsar is a subject of great interest, because astronomers theorize that a neutron star may be producing the pulsations. The Vela pulsar has a magnitude of 24_V. The observation of the Vela pulsar is scheduled over several different times, since various instruments will examine the pulsar. The scheduled observation calls for the High Speed Photometer to observe the pulsar while the HST is in earth shadow, over an eight-hour period. The Wide Field/ Planetary Camera will make a parallel observation, partly to provide a photograph of the stars in the Vela region for the Faint Object Spectrograph. The spectrograph, scheduled to study the pulsar later, can use the camera's photograph to assist in target pointing, since the spectrograph has a much smaller aperture and pointing must be more precise than for the WF/PC.

The Vela pulsar is located about 45 degrees below the celestial equator. The HST will begin slewing to point toward the general celestial region of the Vela pulsar. Because the pulsar is such a faint object, the STOCC and the observer will direct the overall target acquisition (Mode 1), communicating through the TDRS satellite. The coarse targeting will be based on images of the region taken earlier by the WF/PC.

The pointing system will search for the guide stars that will place the light from the Vela pulsar into the correct apertures. The HST reaction wheel assemblies change their speed of rotation, and the change provides the momentum needed for the slew. It will take a few minutes to complete the maneuver and to settle into the new position. Then the HST remains stable while the FGSs spiral-scan out from the FGS FOV to a maximum angle of 90-arcsec as the sensors search for the guide stars.

Once the guide stars finally are targeted, the Space Telescope scientific instruments can observe the pulsar. The ground computers already will have taken the camera image and computed the coordinates for the center of the pulsar. These coordinates will be transmitted to the telescope as small-angle slews needed to place the target into the HSP aperture. The HST will move very slightly, measured in a few arcsecs. Each maneuver will take seconds, with the total less than three minutes to lock the pulsar light onto the HSP aperture. If the TDRS satellite is in position, the photometer immediately will begin sending light-intensity data. The camera will send its data in one burst as the HST passes out of the shadow.

This cycle will continue over the next eight hours: about 40 minutes of data collection and 50 minutes of waiting as the HST passes out of earth shadow (see Figure 4-27). Information from the Vela pulsar will follow the transmission path already described.

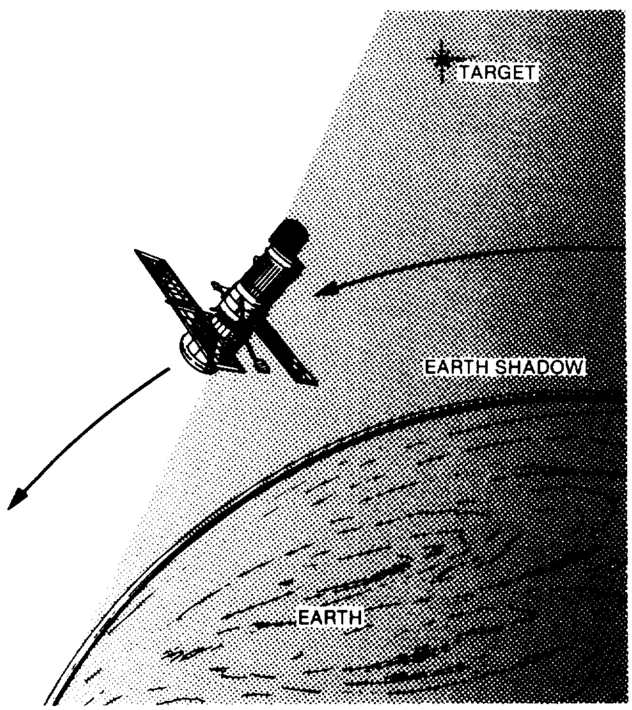


Figure 4–27 HST Passes Out of Shadow

4.4.2.2 Supernova. The Science Institute expects targets of opportunity, unscheduled celestial events, to occur throughout the life of the mission. The chances are good that one such opportune target will be a recently-discovered supernova.

The process of tracking and pointing at an unexpected source is different from a planned observation. The HST may be pointing in an entirely different direction, there may be no guide stars selected for that region of the sky, and the communication satellites may be unavailable because of other commitments. A supernova takes only a few days to peak, so there would be little time to prepare targeting information.

If astronomers make an unexpected supernova sighting, the STScI director must agree with the observing astronomer to reschedule any current observations. Then the STOCC will take a "finding" image of the supernova sky area with the Wide Field Camera, after the HST maneuvers to point the camera in the proper direction. The STOCC will request emergency TDRSS support, while the camera image is analyzed by the consulting astronomers. The supernova might appear as an extremely bright star exploding (see the rendering in Figure 4-28).

The Institute will study the mission schedule, orbital path, and instrument limits to select a favorable observation of a newly-detected supernova. The STScI software will search for guide stars, then calculate the time exposures required for the best data results from the chosen instrument.

The GSSS charts and camera information will produce a set of coordinates to be converted into maneuvering commands sent to the HST. Mode 1 acquisition probably will be used.

Since the HST already will be coarsely pointed for the camera shot, it will slew until it captures the target guide star. Then the guidance sensors will lock onto the guide stars. Light from the supernova will pass into a targeting aperture for calculations to adjust the light precisely into the data aperture. A few moments later the first data will come from the new supernova into the Data Capture Facility.

The data accumulated on the supernova will go into SOGS and be processed in the regular manner.

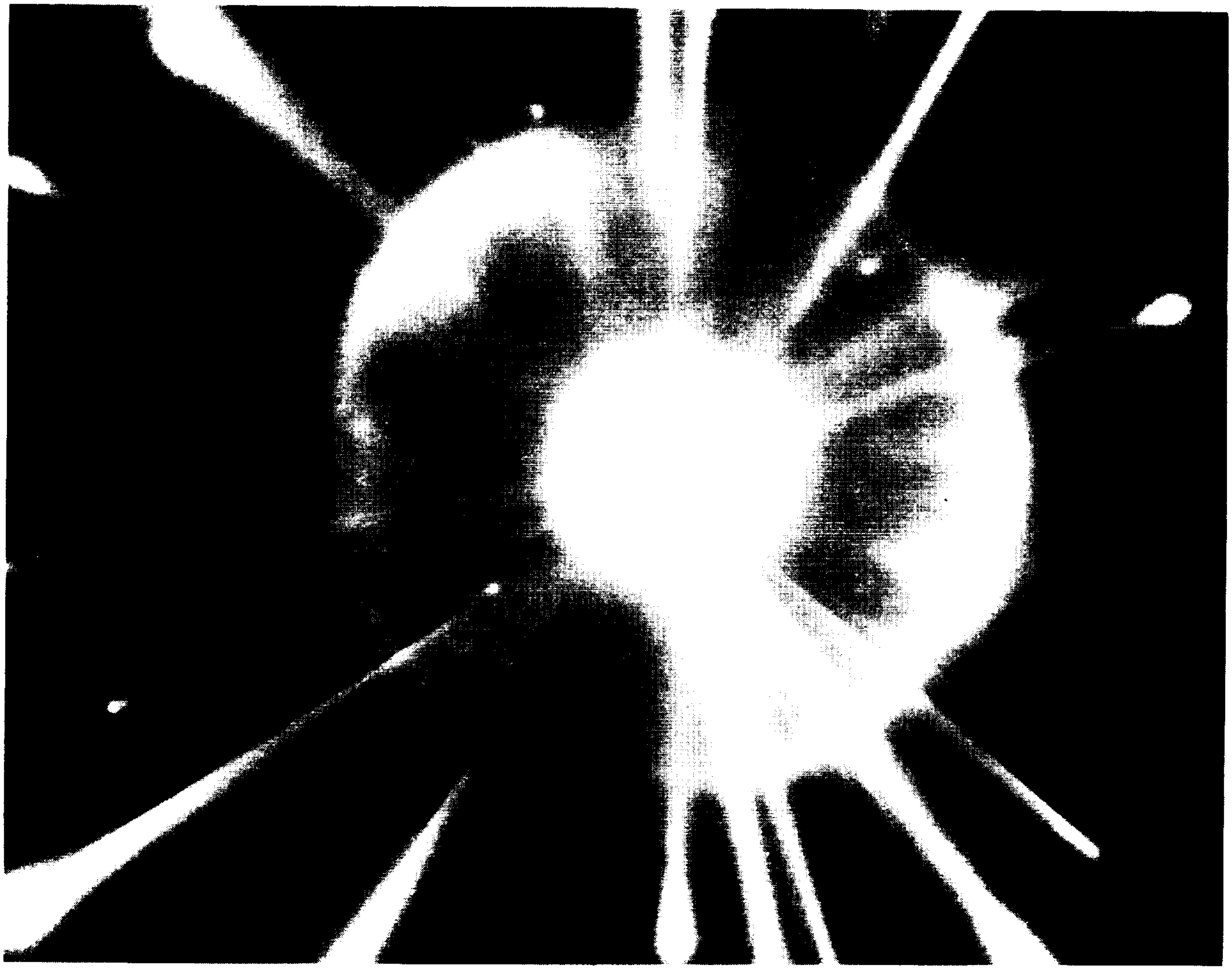


Figure 4–28 WF/PC Image of a Nova

Section 5
HUBBLE SPACE TELESCOPE PROGRAM MANAGEMENT

Managing the Hubble Space Telescope satellite project is a team of government and private participants. The primary members are the National Aeronautics and Space Administration (NASA), the Space Telescope Science Institute (STSci), Lockheed Missiles & Space Company (LMSC), Perkin-Elmer Corporation (P-E), and the instrument development teams (IDIs) and the subcontractors that designed and/or built the Space Telescope's scientific instruments.

5.1 RESPONSIBILITIES

The interlocking responsibilities of the Hubble Space Telescope management team members participating in the development, launch and deployment, and operation of the Hubble Space Telescope are charted in Fig. 5-1.

5.1.1 NASA Responsibilities

NASA has many offices and centers sharing responsibility for the development, launch and deployment, and operation of the Space Telescope. These responsibilities range from overseeing the financial and management aspects of the project to specific responsibility for a single function, such as launching the Shuttle with the HST aboard.

NASA responsibilities are detailed below.

5.1.1.1 NASA Headquarters. The NASA Office of Space Science and Applications (OSSA), in Washington, D.C., plans and directs the agency's entire space science program. The authority for the Space Telescope project lies with the director of the Astrophysics Division (AD). A Space Telescope program manager maintains policies and goals for the project, and administers NASA resources for the Space Telescope program. The HST program scientist oversees overall science policy.

5.1.1.2 Marshall Space Flight Center. Marshall Space Flight Center (MSFC), in Huntsville, AL, is the project management (lead) center. MSFC has been charged with the development of the Space Telescope and the Orbital Verification period after the Shuttle deploys the HST. MSFC is responsible for meeting the cost, schedule, and technical performance goals of the Space Telescope. It also manages the HST cost and schedule of the other elements involved in the project.

5.1.1.3 Goddard Space Flight Center. Goddard will oversee the Scientific Verification, working very closely with the Science Institute on tests developed by Goddard, the STScI, P-E, and Lockheed. Through the Space Telescope ground system, Goddard will control the day-to-day operations of the spacecraft. See Chapter 4 for more information about the ground system.

5.1.1.4 Johnson Space Center. The Johnson Space Center (JSC), in Houston, TX, is responsible for the Space Shuttle Orbiter flight operation. In the HST project, JSC's responsibilities also include all interface requirements between the Orbiter and the Space Telescope payload. JSC also oversees crew training for specific HST support maneuvers, such as maintenance or contingency operation.

Once launched, the Orbiter will communicate with the Space Telescope Operations Control Center (STOCC) through Johnson's Mission Control Center. JSC will be responsible for specific Orbiter flight operations involving the crew, and interacting with STOCC when the crew manipulates the HST. The Mission Control Center will perform Orbiter flight

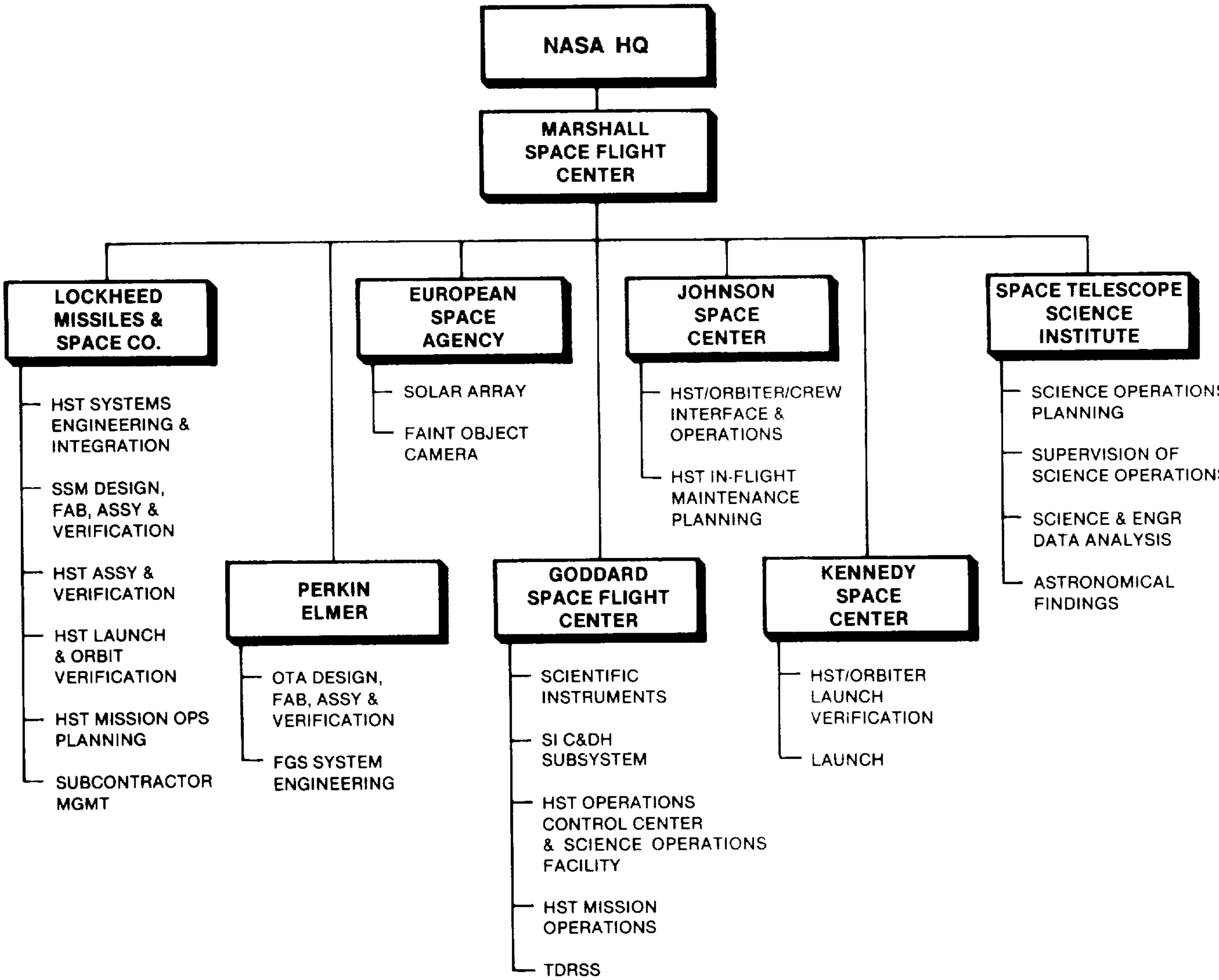


Figure 5–1 Space Telescope Responsibilities

operations on the deployment flight and on maintenance and reboost flights.

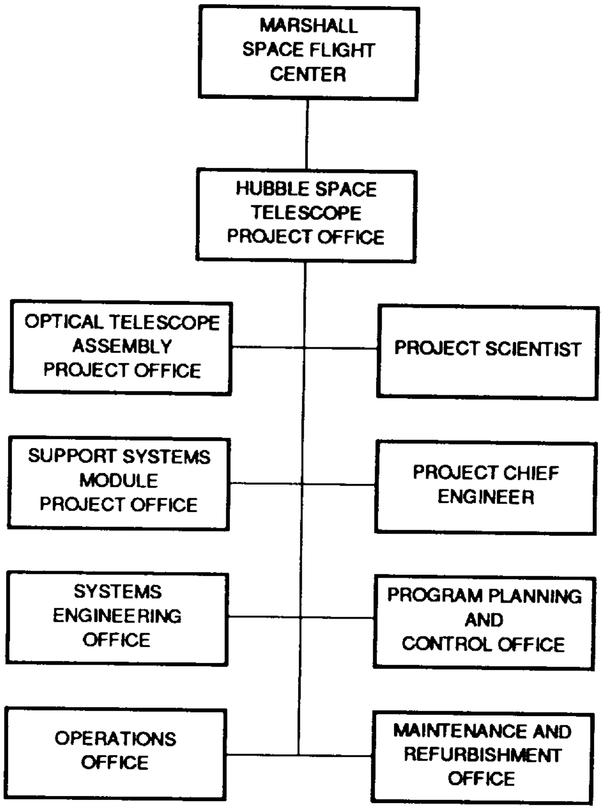
5.1.1.5 Kennedy Space Center. Kennedy Space Center, at Cape Canaveral, FL, is the launch site for Shuttle flights. Kennedy also is responsible for the prelaunch activities, such as placing the Space Telescope in the Orbiter cargo bay.

5.1.1.6 Other NASA Facilities. The Space Telescope project will rely on the Tracking and Data Relay Satellite System (TRDSS) and NASA commercial satellites (NASCOM) for most ground-to-spacecraft communication. The Office of Space Tracking and Data Systems manages these operations.

5.1.2 Space Telescope Science Institute

The major responsibilities of the Space Telescope Science Institute are to manage the science program and coordinate Space Telescope operations with the STOCC, the Institute's counterpart in the Space Telescope ground system.

The science program involves setting goals for the HST observations, selecting the observa-



MSFC RESPONSIBILITIES

- HST DEVELOPMENT LEAD CENTER
- TOTAL PROJECT MANAGEMENT
- OTA DEVELOPMENT
- SSM DEVELOPMENT
- HST INTEGRATION AND VERIFICATION
- ORBITAL VERIFICATION OPERATIONS
- MAINTENANCE AND REFURBISHMENT PLANNING

Figure 5–2 MSFC Space Telescope Organization

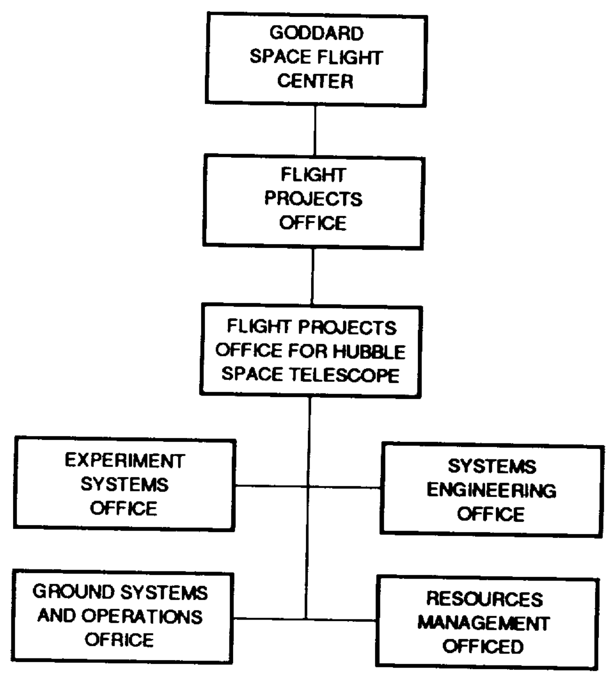
tion plans that best accomplish those goals, interweaving all the selected observations into a cohesive and interactive schedule, conducting the science operations through the STOCC, and processing the data produced by the spacecraft's scientific instruments.

Time management will be important to the Institute, because it already has far more observation requests than it can fill. In addition, the teams that produced the scientific instruments all have guaranteed observation time. To handle this management problem, the STScI is using sophisticated software to analyze all time-management factors and make amenable compromises.

The Institute has participated in the preparation of the scientific instruments, assisting in the development of the instruments from an astronomical basis, and in the creation of verification tests.

5.1.3 Lockheed Missiles & Space Company

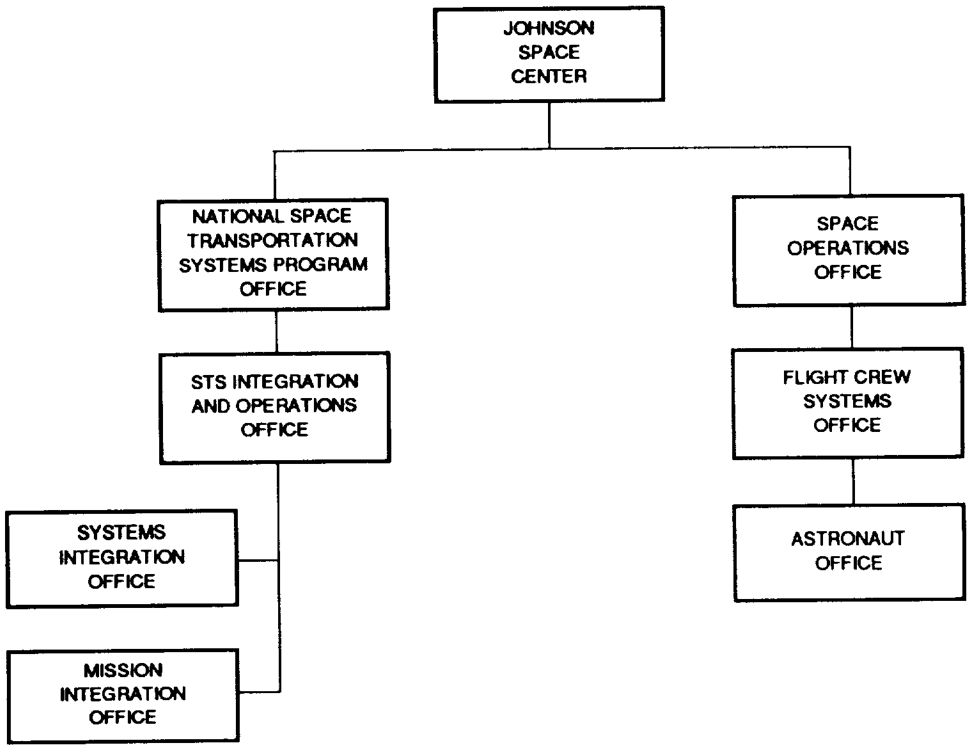
Lockheed Missiles & Space Company (LMSC), in Sunnyvale, CA, is the contractor for the development of the Support Systems Module. LMSC is the co-prime contractor and supervised the work of many subcontractors. The LMSC contract includes design, development, fabrication and assembly, and verification of



GSFC RESPONSIBILITIES

- SCIENCE INSTRUMENTS DEVELOPMENT
- GROUND OPERATIONS SYSTEMS DEVELOPMENT
- SCIENCE VERIFICATION OPERATIONS
- HST OPERATIONS
- M&R PLANNING SUPPORT

Figure 5–3 GSFC Space Telescope Organization



JSC RESPONSIBILITIES:

- HST TO SHUTTLE INTERFACES
  - SHUTTLE SYSTEMS INTEGRATION
  - SHUTTLE MISSION INTEGRATION
- SHUTTLE ORBITER MISSION OPERATIONS
- HST TO SHUTTLE CREW INTERFACES
  - HST DEPLOYMENT
  - HST M&R PLANNING SUPPORT

Figure 5–4 JSC Space Telescope Organization

the SSM; integration of all Hubble Space Telescope components; integration testing of the HST once assembled; and support for NASA during ground, flight, and orbital operations. Lockheed will also serve as the HST Missions Operations Contractor (MOC) at the Goddard Space Flight Center. Lockheed controllers will control and communicate with the telescope from the missions operations room in the Space Telescope Operations Control Center (STOCC) at Goddard.

5.1.4 Perkin-Elmer Corporation

Perkin-Elmer Corporation (P-E), of Danbury, Connecticut, the Space Telescope project's other coprime contractor, was acquired recently by Hughes and is now called Hughes Danbury Optical Systems, Inc. The company is responsible for the Optical Telescope Assembly, from design and development through verification testing and delivery to Lockheed for integration with the other HST components. They also developed the fine guidance sensors.

5.1.5 Scientific Instrument Contractors

NASA contracted with specific principal investigators and subcontractors to develop and build each scientific instrument. The principal investigator in each case is responsible for the

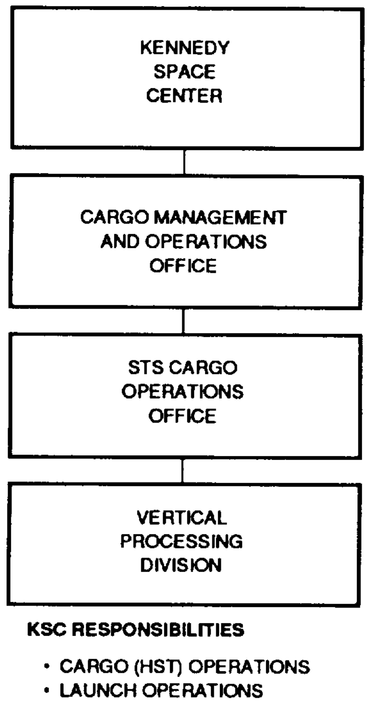


Figure 5–5 KSC Space Telescope Organization

design and operation of the specific instrument. In return, the principal investigator receives primary observing time during the first months of the Space Telescope's operational life.

Each subcontractor works with the principal investigator as an instrument development team to develop final working instruments from the design. In some cases, the PI and subcontractor are part of the same organization. An example is the team of Dr. Robert Bless at the University of Wisconsin, responsible for the High Speed Photometer. In all cases, the instrument development teams worked closely with NASA and the Space Telescope Science Institute to assure the development of instruments that can fulfill the Space Telescope mission goals.

The instrument development teams are listed in Table 5-1.

5.2 CONTRACTOR CONTRIBUTIONS

Many contractors and subcontractors contributed to the development of the Hubble Space Telescope. The contractors, subcontractors, and their contribution to the project are listed in Table 5-2.

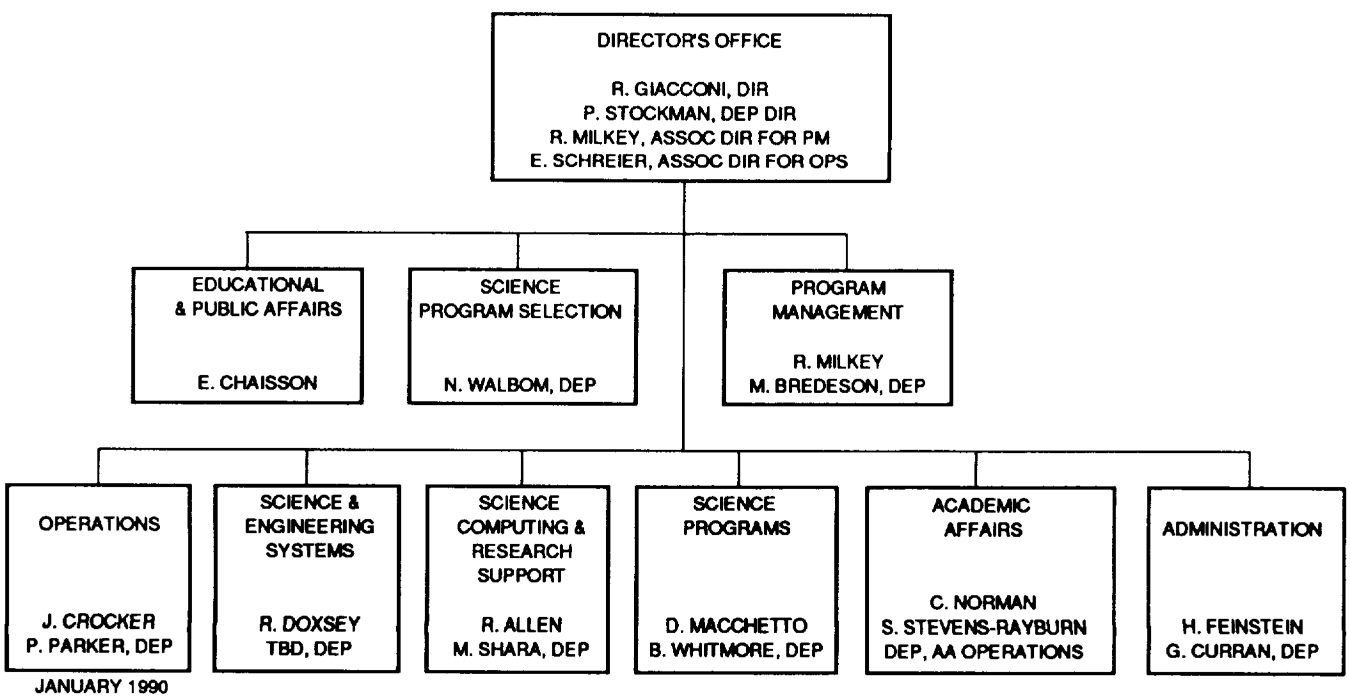


Figure 5–6 STSci Organization

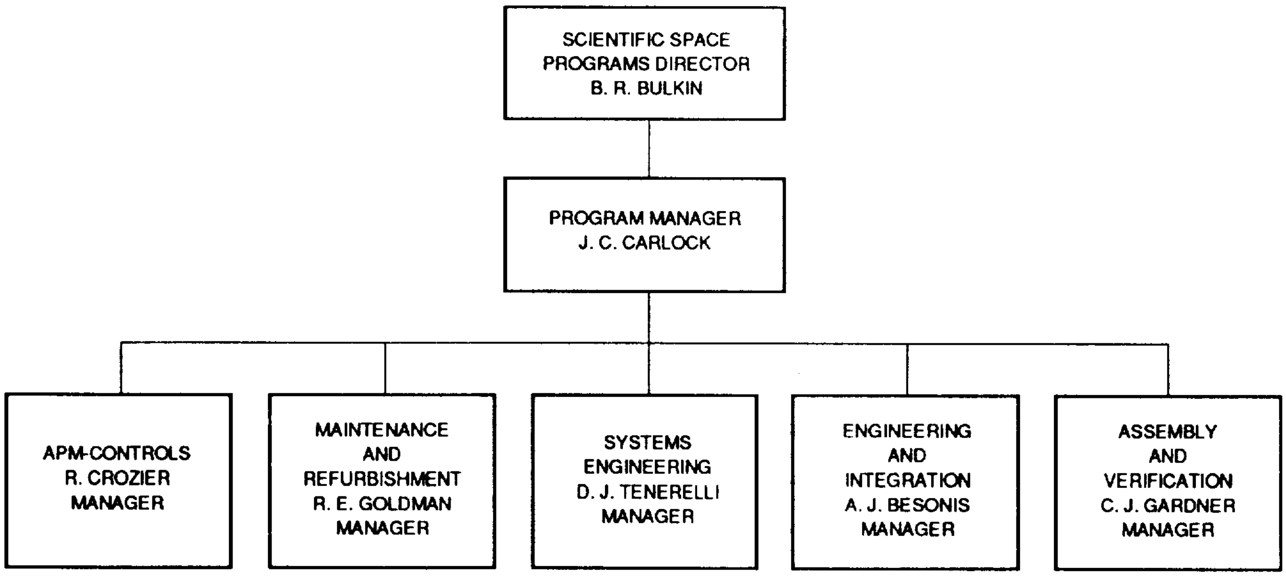


Figure 5–7 LMSC Space Telescope Organization

Table 5–1 Instrument Development Teams (IDTs)

Instrument/ Team	Faint Object Camera	Faint Object Spectrograph	Goddard High Resolution Spectrograph	High Speed Photometer	Wide Field/ Planetary Camera
Principal Investigator	F. D. Macchetto, European Space Agency	R. J. Harms, Applied Research Corp.	J. C. Brandt, Goddard Space Flight Center	R. C. Bless, University of Wisconsin	J. A. Westphal, California Institute of Technology
Subcontractor	Dornier Corporation British Aerospace Matra-Espace	Martin Marietta Corporation	Ball Aerospace	Space Astronomy Lab, University of Wisconsin	Jet Propulsion Lab

HUGHES DANBURY OPTICAL SYSTEMS
HUBBLE SPACE TELESCOPE, OPTICAL TELESCOPE ASSEMBLY PROGRAM MANAGEMENT

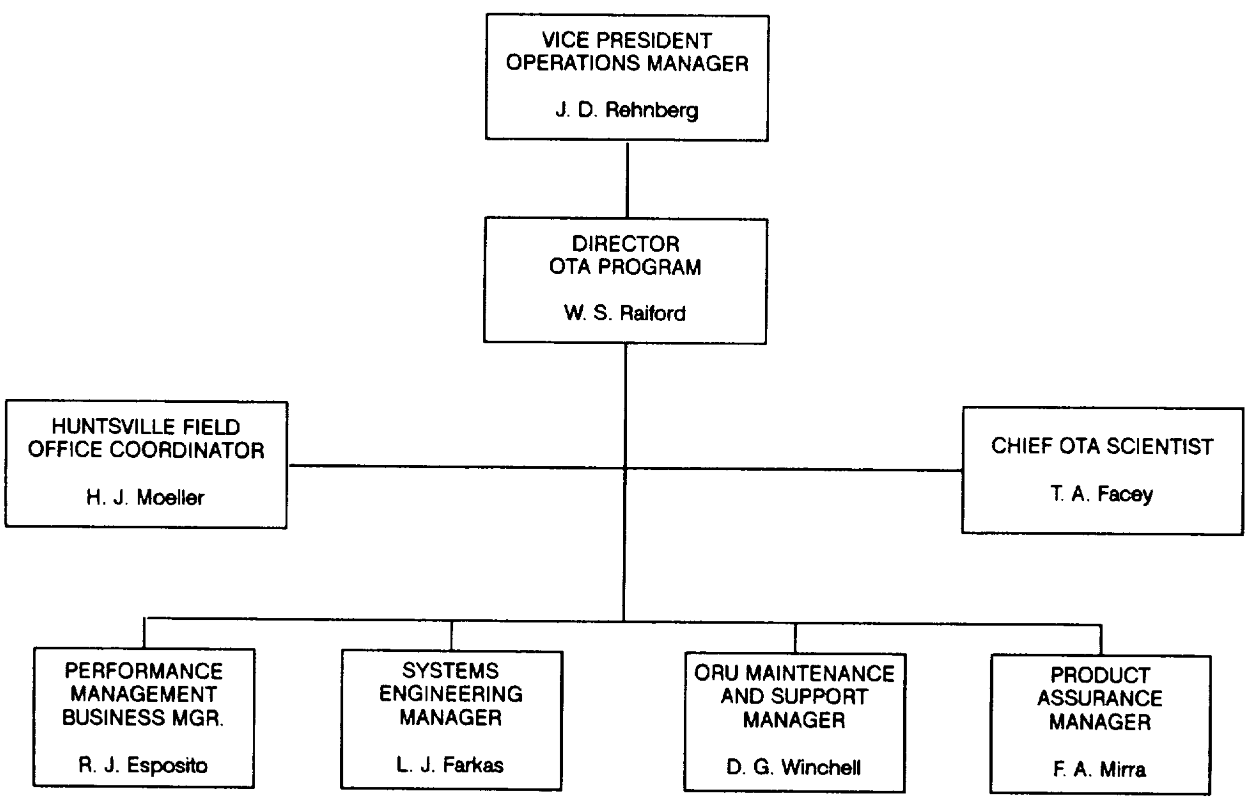


Figure 5–8 Hughes Space Telescope Organization

Table 5–2 Space Telescope Equipment Responsibilities

Equipment	Contractor
Actuator Control Electronics	P-E
Aft Latch, Solar Array	LMSC
Antenna Pointing System	Sperry
Battery	Eagle Picher/GE
Charge Current Controller	LMSC
Circulator Switch	Electromagnetic
Coarse Sun Sensor	LMSC
Computer	Rockwell Autonetics
Data Interface Unit	LMSC
Data Management Unit	LMSC
Deployment Control Electronics	ESA
Dish and Feed for HGA	GE
Elec. Power/Thermal Control Elect.	P-E
FHST Light Shade	Bendix
Faint Object Camera	Dornier
Faint Object Spectrograph	MMC
Fine Guidance Electronics	Harris
Fine Guidance Sensor	P-E
Fixed Head Star Tracker	Ball/Bendix
Focal Plane Assembly	P-E
Forward Latch, Solar Array	LMSC
Goddard High Resolution Spectrograph	Ball Aerospace
High Speed Photometer	Univ. Of Wis.
Hinge, Aperture Door	LMSC
Hinge, High Gain Antenna	LMSC
Image Dissector Camera Assembly	P-E
Instrument Control Unit	LMSC
Interconnect Cables	LMSC/P-E et al.
Latch, Aperture Door	LMSC
Latch, High Gain Antenna	LMSC
Low Gain Antenna	LMSC
MA Transponder	Motorola
Magnetic Torquer	Ithaco/Bendix
Magnetic Sensing System	Schoenstadt/Bendix
Mechanism Control Unit	LMSC
Metal Matrix Mast	DWA/LMSC
Multilayer Insulation	LMSC/P-E
Off Load Device	ESA
Optical Telescope Assembly	P-E
Optical Control Electronics	P-E
Oscillator	Frequency Elect.
Photomultiplier Tube Electronics	P-E
Pointing Safemode Electronics Assembly	Bendix
Power Control Unit	LMSC
Power Distribution Unit	LMSC
Primary Deployment Mechanism	ESA
Primary Mirror Assembly	P-E
RF Multiplexer	Wavecom
RF Switch	Transco
RF Transfer Switch	Transco
Rate Gyro Assembly	Bendix
Reaction Wheel Assembly	Sperry
Retrieval Mode Assembly	Northrop/Bendix
Rotary Drive	Schaeffer
SAD Adapter	ESA
SI C&DH	Fairchild/IBM
SSA Transmitter	Cubic
Science/Engineering Tape Recorder	Odetics
Secondary Deployment Mechanism	ESA
Secondary Mirror Assembly	P-E
Sensor Electronics Assembly	P-E
Solar Array Blanket	ESA
Solar Array Drive	ESA
Solar Array Drive Electronics	ESA
Star Selector Servo	BEI
Temperature Sensor	LMSC/P-E
Thermostat/Heater	LMSC/P-E
Umbilical Drive Unit	Sperry
Waveguide	LMSC
Wide Field/Planetary Camera	JPL

Appendix A
ASTRONOMICAL CONCEPTS

The following discussion briefly presents astronomical concepts that relate to specific discussions of the Hubble Space Telescope instruments and observations.

A.1 ENERGY AND WAVELENGTH

All celestial objects radiate energy except black holes. Light is one portion of electromagnetic energy released by an object as it burns up its matter. The sun, for example, burns mostly hydrogen. The hotter the object, the more energy radiated by that object.

Energy has a dual existence: it is a constant stream of particles called photons, and it is a wave. They both exist together, yet each is separate. Photons are discrete units of electromagnetic energy, measured by counting electrons released by the photons when they strike certain materials. The light detectors used in the HST operate this way, channeling photons through chemically-coated windows and counting the released electrons.

In some respect waves of electromagnetic energy are like waves in water. The wave's length is measured from the peak, or crest, of one wave to the peak of the next wave. The length of a wave depends upon the temperature of its source. The hotter the source, the shorter the wavelength. Different elements radiate energy at different temperatures, and each has a unique wavelength pattern. A star will produce different wavelengths depending upon the star's temperature and on what elements exist within the star to become heated and radiate energy.

Because stars contain many elements, stars radiate a broad range of energy, called a wavelength spectrum. Astronomers study the spectrum of energy coming from stars to discover, from the distinct patterns, what chemicals are radiating energy in the star and how hot the star is. The spectrum goes from the shortest wavelengths, called gamma rays, to the longest wavelengths, called radio waves. The visible wavelengths are the colors from short violet rays to red, the longest visible rays of energy. A star will appear the color corresponding to the wavelength at which the peak energy is emitted. For example, a star that burns at a cooler, 3000 degree Kelvin (K) will appear reddish. A 12,000 degree K star will appear blue. Both stars may still be producing an even more energetic component of emissions, such as gamma rays, that are invisible.

Light wavelengths have another property that plays an important part in the way astronomers study the universe. As the electric and magnetic field components of light propagate, they vibrate randomly in planes perpendicular to the direction of motion. Figure A-1 illustrates the vibration of these components of polarized light.

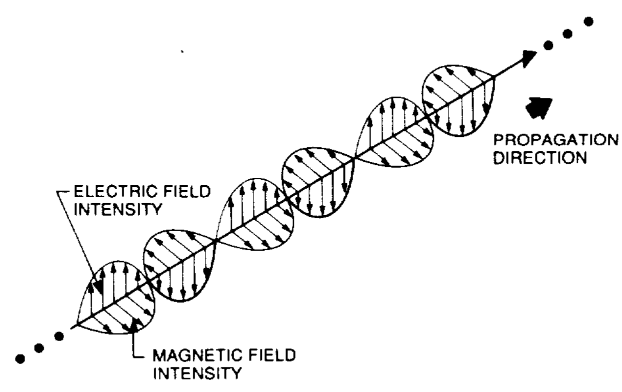


Figure A–1 Polarized Light

In certain situations, however, light passes through magnetized dust clouds where the alignment of the cloud particles scatters light according to the spatial orientation of the electrical and magnetic field components of the light waves. An observer looking in a specific direction detects this polarized light. Tracing its path can lead to the discovery of gigantic magnetic fields in space.

A.1.1 Measuring Wavelengths

Wavelengths are measured in units called angstroms (Å). There are 10 billion angstrom units in one meter. (Another measurement is the nanometer; there are 10 Å per nanometer.) Wavelength sizes range from a few angstroms for the most energetic gamma rays to hundreds of thousands of angstroms for long radio waves. Visible light covers the spectral range from 4000-7000 Angstroms.

Most electromagnetic wavelengths are invisible to the human eye. Some of the visible wavelengths are blocked by dust and gases in the earth's atmosphere. So the visible starlight detected on earth is just a small portion of the entire spectrum of energy radiated by that object. The Hubble Space Telescope, because it will be orbiting above the atmosphere, can detect even the wavelengths invisible to the strongest earth telescopes. The HST instruments measure wavelengths from 1100 Å, in the ultraviolet, to 11,000 Å, in the infrared. See Figure A-2 for a graphic illustration.

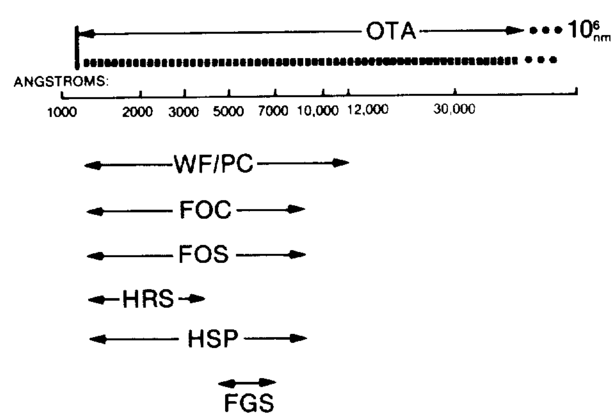


Figure A–2 HST Wavelength Ranges

A.1.2 Resolving Wavelengths

Spectral resolution determines how well closely-spaced features in the spectrum can be detected. Spectral resolution is calculated by measuring the distance between the two closest wavelength peaks that can be distinguished, then dividing that distance into the wavelength. For example, a spectral resolution of 2000 means you can see separate wavelengths at 2000 Å, 2001 Å, 2002 Å, and so on. These spectral features yield information concerning physical conditions at the astronomical target.

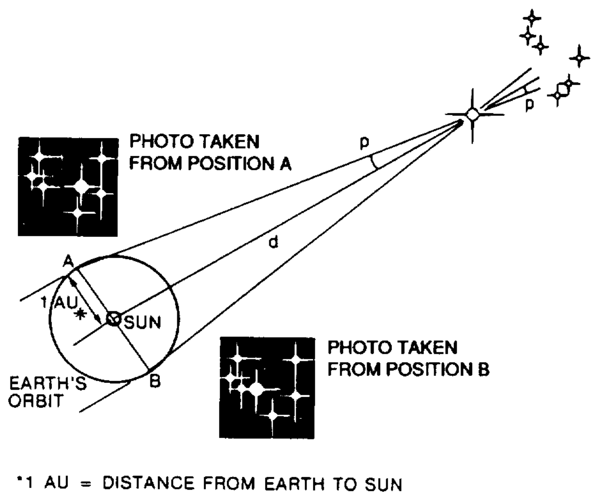
A.2 MEASURING STARS

The basic unit measuring the distance from a star is the light year: the distance light can travel in one year, which is approximately six trillion miles. Distance to nearby stars is calculated by measuring the star's parallax. Parallax is the "apparent" angular displacement of an object, when in reality the observer's movement caused the perceived change in position of the object.

Astronomers view stars from two positions and calculate the angle between the star's "motion" or change in position against more distant background objects. One-half that angle is called the stellar parallax. A star's distance can then be calculated using simple geometry (Figure A-3).

Parallax measurements can be made only for stars relatively near us, generally within 200 parsecs (650 light years). For greater distances, the parallax angle is too small to measure. Other methods exist, including using temperatures and intensity of light, to extrapolate distance.

Another type of measurement, angular or spatial resolution, determines how clearly an instrument forms an image. It is a measure of the fineness of detail in the image. The greater the angular resolution, the closer two objects can appear and still be distinguished. Angular



Note that the foreground star in Position B appears to have shifted position with respect to the "fixed" background stars by an angular displacement of 2p. The parallax of this star is "p", measured in seconds of arc; it is the angle opposite to and bounded at the star by the baseline distance 1 au.

Figure A-3 Calculating a Star's Parallax

resolution is measured in terms of the components of a circle: 360 degrees, 60 arcminutes to make up one degree, and 60 seconds of arc to make up one arcminute.

To illustrate, the angular resolution between stars is measured in arcseconds by the SIs. The finest spatial resolution obtainable with the HST is about one-hundredth of one second of arc, ten times better than the largest earth-based telescopes. In addition, astronomers measure the scientific instruments' field of view in arcseconds and arcminutes. Further, the pointing stability of the telescope is calculated in arcseconds. See Figure A-4.

The brightness (magnitude) of a celestial object is one of the parameters measured by a telescope, with the appropriate instrumentation. Magnitude is measured two ways: apparent and absolute. Apparent visual magnitude is how bright a star appears without any correction made for its distance. Absolute magnitude is how bright the star would appear if it were viewed placed at a standard distance (10 parsecs). Hence, absolute magnitudes compare the intrinsic luminosities of objects, removing the dilution of brightness by increasing distance. Magnitude measurement goes from minus figures for the brightest objects to plus figures for faint objects. The magnitude scale, thus, is inverted: large positive numbers indicate faint (low brightness) objects.

For example, the sun is -26 apparent visual magnitude, but if you viewed it from 10 parsecs (the standard distance for absolute magnitude) the sun would be barely visible at a magnitude of +4.85. Absolute magnitude is signified by M_V; apparent magnitude by m_V. The faintest star visible to the unaided eye is about 6 apparent magnitude (m_V); the Hale Telescope on Mount Palomar detects stars at $23m_V$; the HST will see stars at $28m_V$ or fainter.

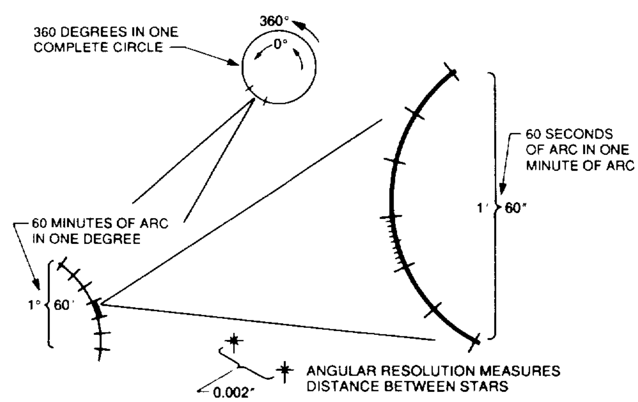


Figure A-4 Angular Measurement

A.3 UNIVERSE EXPANSION

One of the key issues for investigation by the Space Telescope is the future of the universe. Currently the universe is expanding from the explosion astronomers call the Big Bang. Edwin P. Hubble, for whom the Space Telescope is named, calculated that the velocity of that expansion equals a constant (H) times a galaxy's distance from us. Figure A-5 charts the Hubble Law.

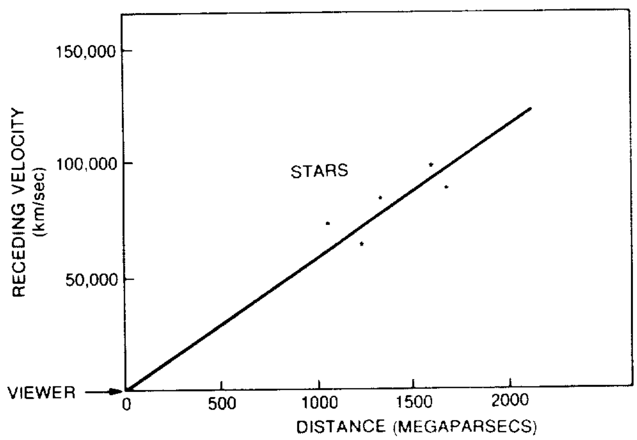


Figure A-5 The Hubble Law

Astronomers calculate that the universe is still expanding, but possibly more slowly than right after the Big Bang. If it slows enough, the universe may eventually fall back on itself in a "Big Crunch." One indication of a slowing rate of expansion would be a decrease in the Hubble constant. To confirm this, however, astronomers must measure H accurately, which in turn requires measuring distances and receding galactic velocities (called redshifts) accurately. Only then can astronomers compare distances and redshifts, through studying galactic movement, to see whether the universe is slowing its rate of expansion. This is a major goal for the Hubble Space Telescope.

Appendix B
ACRONYMS/ABBREVIATIONS

Å	Angstrom
AB	Aft Bulkhead
ACE	Actuator Control Electronics
ACS	Actuator Control Subsystem
AD	Aperture Door
Al	Aluminum
AS	Aft Shroud
BCU	Bus Coupler Unit
C	Celsius
CCC	Charge Current Controller
CCD	Charge-Coupled Device
CDI	Command Data Interface
CEI	Contract End Item
CIT	California Institute of Technology
CMD	Command
cm	Centimeter
CPC	Computer Program Command
CPM	Central Processor Module
CPU	Central Processing Unit
CRT	Cathode Ray Tube
CSS	Coarse Sun Sensor
CU	Control Unit
CU/SDF	Control Unit/Science Data Formatter
DCE	Deployment Control Electronics
DCF	Data Capture Facility
DIU	Data Interface Unit
DMA	Direct Memory Access
DMS	Data Management Subsystem
DMU	Data Management Unit
EBA	Electronics Bay Assembly
EBS	Electron Bombarded Silicon
ECA	Electronics Control Assembly
ECU	Electronics Control Unit
EOR	End of Record
EPS	Electrical Power Subsystem
EPTCE	Electrical Power Thermal Control Electronics
ES	Equipment Section
ESA	European Space Agency
EVA	Extravehicular Activity

F	Fahrenheit
FCA	Figure Control Actuator
FGE	Fine Guidance Electronics
FGS	Fine Guidance Sensor
FHST	Fixed Head Star Tracker
FOC	Faint Object Camera
FOS	Faint Object Spectrograph
FOSR	Flexible Optical Solar Reflector
FOV	Field of View
FPS	Focal Plane Structure
FPSA	Focal Plane Structure Assembly
FS	Forward Shell
FSS	Flight Support Structure
ft	Feet
G/E	Graphite-Epoxy
GE	General Electric
GGM	Gravity Gradient Mode
GSFC	Goddard Space Flight Center (Maryland)
GSTDN	Ground Spaceflight Tracking and Data Network
HGA	High Gain Antenna
HRS	High Resolution Spectrograph
HSP	High Speed Photometer
HST	Hubble Space Telescope
Hz	Hertz (Cycles per Second)
I&C	Instrumentation and Communications (Subsystem)
IBM	International Business Machines Corporation
IDT	Image Dissector Tube/Instrument Development Team
in	Inches
IOU	Input Output Unit
IR	Infrared
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
k	Kilo (1000)
kbytes	Kilobytes
kg	Kilogram
km	Kilometer
KSC	Kennedy Space Center
lb	Pound
LGA	Low Gain Antenna

LMSC	Lockheed Missiles & Space Company, Inc.
LOS	Line of Sight
LS	Light Shield
m	Meter
MA	Multiple Access
MAT	Multiple Access Transponder
M&R	Maintenance and Refurbishment
MCU	Mechanisms Control Unit
MDB	Multiplexed Data Bus
MgF^2	Magnesium Fluoride
MHz	Megahertz
mi	Miles
MLI	Multilayer Insulation
mm	Millimeter
MM	Maintenance Mission
MMC	Martin Marietta Corporation
MP	Maintenance Platform
MR	Main Ring
MRA	Main Ring Assembly
MSFC	Marshall Space Flight Center
MSS	Magnetic Sensing System
MTA	Metering Truss Assembly
MTS	Metering Truss Structure
MU	Memory Unit
M_V	Absolute Visual Magnitude
m_V	Apparent Visual Magnitude
NASA	National Aeronautics and Space Administration
NASCOM	NASA Communications Network
NCC	Network Control Center
nm	Nanometers
nm	nautical miles
NSSC-I	NASA Standard Spacecraft Computer, Model-I
OCE	Optical Control Electronics
OCS	Optical Control Subsystem
ORU	Orbital Replaceable Unit
OTA	Optical Telescope Assembly
P-E	Perkin-Elmer Corporation
PC	Planetary Camera
PCEA	Pointing Control Electronics Assembly
PCS	Pointing Control Subsystem
PCU	Power Control Unit; Power Convertor Unit (module of DF-224)
PDA	Photon Detector Assembly

PDM	Primary Deployment Mechanism
PDU	Power Distribution Unit
PI	Principal Investigator; Payload Interrogator
PIT	Processor Interface Table
PM	Primary Mirror
PMA	Primary Mirror Assembly
PMT	Photomultiplier Tube
PN	Pseudo-Random Noise
POCC	Payload Operations Control Center
PSEA	Pointing/Safemode Electronics Assembly
PWR	Power
RAM	Random-Access Memory
RBM	Radial Bay Module
RGA	Rate Gyro Assembly
RIU	Remote Interface Unit
RM	Remote Module
RMGA	Retrieval Mode Gyro Assembly
RMS	Remote Manipulator System
ROM	Read-Only Memory
RS	Reed-Solomon
RSU	Rate Sensing Unit
RWA	Reaction Wheel Assembly
S&M	Structures and Mechanical (Subsystem)
S/N	Signal-to-Noise Ratio
SA	Solar Array
SAT	Single Access Transponder
SAA	South Atlantic Anomaly
SAD	Solar Array Drive
SADE	Solar Array Drive Electronics
SADM	Solar Array Drive Mechanism
SBA	Secondary Baffle Assembly
SCP	Stored Command Processor
SD	Science Data
SDF	Science Data Formatter
SDM	Secondary Deployment Mechanism
SI	Scientific Instrument
SI C&DH	SI Control and Data Handling (Subsystem)
SiO_2	Silicon Dioxide
SIPE	Scientific Instrument Payload Enclosure
SM	Secondary Mirror
SMA	Secondary Mirror Assembly
SPC	Stored Program Command
SSC	Science Support Center
SSE	Space Support Equipment

SSM	Support Systems Module
SSM-ES	SSM-Equipment Section
SSP	Standard Switch Panel
SS	Safing System
STDN	Space (flight) Tracking and Data Network
STINT	Standard Interface
STOCC	Space Telescope Operations Control Center
STS	Space Transportation System
STScI	Space Telescope Science Institute
TCE	Thermal Control Electronics
TCS	Thermal Control Subsystem
TDRS	Tracking and Data Relay Satellite
TDRSS	Tracking and Data Relay Satellite System
TiO_2	Titanium Dioxide
TLM	Telemetry
TRW	Thompson Ramo Woolridge, Inc.
TYP	Typical
UCSD	University of California, San Diego
ULE	Ultra Low Expansion
m	Micrometer, one millionth of a meter
UV	Ultraviolet
V	Volt
V1,V2,V3	HST Axes
W	Watt
WFC	Wide Field Camera
WF/PC	Wide Field/Planetary Camera
WT	Weight
ZOE	Zone of Exclusion

Appendix C
GLOSSARY OF TERMS

- A -

Acquisition, target	Adjusting the HST position to place incoming target light in an instrument's aperture.
Aft	The rear of the spacecraft.
Altitude	Height in space.
Aplanatic	Image corrected everywhere in the field of view.
Aperture	Opening that allows light to fall onto an instrument's optics.
Arcsec	A wedge of angle, 1/3600th of one degree, in the 360–degree "pie" that makes up the sky. An arcminute is 60 seconds; a degree is 60 minutes.
Apodizer	A masking device that blocks stray light
Astigmatism	A defect that prevents sharp focusing.
Astrometry	Measurement of star positions in relation To other stars
Astrophysicist	Scientist who studies the physics of astronomy.
Attitude	Orientation of the spacecraft's axes relative to the earth.

- B -

Baffle	Material that extracts stray light from the incoming image.

- C -

Cassegrain	A type of telescope that reflects or "folds" the incoming light to have a longer focal length in a short physical length.
Changeout	Exchanging a unit on the satellite.
Collimate	To straighten or make parallel two light paths.
Coma	Image abberations that give it a "tail".
Concave	A mirror surface that bends outward to expand an image.
Convex	A mirror surface that bends inward to concentrate an image.
Coronographic	A device that allows viewing a light object's corona.

- D -

Diffraction grating	Split light into a spectrum of the component wavelengths
Drag, atmospheric	Effect of atmosphere that slows a spacecraft and forces its orbit to decay.

- E -

Electron	A small particle of electricity.
Ellipsoid	A surface with only circular planes.
Extravehicular	Outside the spacecraft; activity in space conducted by suited astronauts.

- F -

Focal plane	The axis or geometric plane where the incoming light is focused by the telescope.

- H -

Hyperboloidal	A slightly deeper curve, mathematically, than a parabola; shape of the primary mirror.

- I -

Interstellar	Between celestial objects; often refers to the matter in space that is not a star, such as clouds of dust and gas.

- L -

Light year	The distance traveled by light in one year, approximately six trillion miles.
Luminosity	The intensity of a star's brightness.

- M -

Magnitude, absolute	How bright a star appears without any correction made for its distance.
Magnitude, apparent	How bright the star would appear if it were viewed placed at a standard distance.

- N -

Nebula	A mass of luminous interstellar dust and gas, often produced after a stellar nova.
Nova	The explosion of a star.

- O -

Occultation	Eclipsing one body with another.
Orientation	Position in space relative to the earth.

- P -

Parallax	The "apparent" angular movement of an object, caused in reality by the observer's movement, not the object.
Photon	A unit of electromagnetic energy.
Pixel	A single element of a detection device.
Polarity	Light magnetized to move along certain planes; polarimetric observation studies the light moving along a given plane.
Prism	A device that breaks light into its composite wavelength spectrum.

- Q -

Quasar	A quasi-stellar object of unknown origin or composition.

- R -

Radial	Perpendicular to a plane; i.e., instruments placed at a 90-degree angle from the optical axis of the HST.
Reboost	To boost the satellite back into its original orbit after the orbit has decayed because of atmopspheric drag.
Resolution, spectral	Determines how well closely-spaced features in the wavelength spectrum can be detected.
Resolution, angular	Determines how clearly an instrument forms an image.
Ritchey-Chretien	A type of Cassegrain (folded) telescope where both primary and seconary mirrors are hyperboloidal to correct for image aberrations.

- S -

Spectral devices	A spectrograph is an instrument that photographs the spectrum of light within a wavelength range. A spectrometer measures the position of spectral lines. A spectrophotometer determines energy distribution in a spectrum.
Spectrum	The wavelength range of light in an image.

- T -

Telemetry	Data and commands sent from the spacecraft to the ground stations.

- U - V - W -

Wavelength	The spectral range of light in an image.

Appendix D
NASA SPECIFICATIONS FOR THE HUBBLE SPACE TELESCOPE

The Contract End Item (CEI) Specifications proposed by NASA for the Hubble Space Telescope put exacting demands on each of the subsystems and the scientific instruments. The requirements are in two categories: performance/operating requirements, and viewing/scheduling requirements. In addition, as the mission progresses and knowledge about this project accumulates, new mission-derived requirements will arise.

D.1 PERFORMANCE/OPERATING REQUIREMENTS

These requirements reflect the consideration of mission analyses, trade studies, and evaluations. The most important system requirements are listed below, by system.

Pointing Control System. The PCS operating modes are coarse and fine pointing, solar-system object tracking, scanning, maneuvering, and contingency.

In Coarse Pointing Mode (without the FGS), the PCS will point to within 30 arcsec of a target 99% of the time. In Fine Pointing Mode the PCS will place a target star in any SI entrance aperture with an accuracy of 0.01 arcsec for the length of the observation. The image cannot move more than 0.007 arcsec. In Solar System Object Tracking Mode, the PCS will provide a minimum of three arcmin tracking for objects with an angular velocity of up to 0.21 arcsec per second.

For scanning, the HST should scan fields up to 1 arcmin square at a speed of up to 40 arcsec/sec, for an aperture sized from 0.1 to 10 arcsec.

For maneuvering, the HST will slew 90 degrees in 18 minutes, with two minutes more for settling.

HST Position. The normal spacecraft position will place the sun in the V1-V3 plane on the V3 side of the spacecraft. Viewing positions will be outside 50 degrees of the sun — with no direct sunlight going into the aperture opening, even with a five-degree roll on the V1 axis.

Aperture Door. The door will close if the sun is within 20 degrees of the V1 axis. During normal operation, the door will remain open, but the PCS will not slew to within 70R of the bright limb of the earth or to within 15R of the bright moon.

Data Management Subsystem. The DMS is reprogrammable, with a storage capability of 5000 bytes (words) for commands, 125 million bytes (Mb) for science data, and 12.5 Mb for engineering data. It will receive and merge SI, OTA, and SSM engineering data.

Instrumentation and Communication (I & C) Subsystem. The I&C subsystem will use the multiple-access channel for commands, tracking, and real-time engineering telemetry. High data-rate scientific data will transmit via the single-access channel. The system should be able to transmit science and engineering data simultaneously. The minimum possible transmission time is 20 minutes of scientific data per orbit.

Electrical Power Subsystem. The solar arrays can provide a maximum average power output of 2800 W during each orbit for the OTA and SIs for two years, even if one battery fails. The battery charge drain over 24 hours will be less than 20%, even with one battery out. The battery charger can recharge batteries completely every orbit during normal conditions. After an abnormal roll maneuver, battery energy will replenish completely within five orbits.

Thermal Control Subsystem. The thermal system is passive, protecting all SSM equipment, the OTA, SIs, and SI C&DH. The SSM aft shroud can accommodate heat radiated by dissipating power loads of 300 to 500 W.

SIs, SI C&DH. Scientific instrument power will be less than 150 W for 28V, or 530 W when used with the SI C&DH. A peak power of 750 W for three seconds in any 10-minute period will do no harm.

The number of scientific instruments used together is an operational decision based on power, thermal, and data-management needs.

OTA. The OTA can capture 70% of the incident energy from a star (starlight) within a 0.01 arcsec radius, held for up to 24 hours. The optical image will be at least 38% at 1216 A and 55% at 6328 A; higher spectral ranges make up the rest to 70%. The OTA can resolve point sources (a single object) of at least $27m_V$ with a signal-to-noise (S/N) ratio of 10 after four hours integration time. For extended objects like galaxies, the surface brightness can be at least 25 $m_V/arcsec^2$, resolved to at least 0.25 arcmin with a S/N ratio of 10 for 10 hours integration time.

Stray light at the focal plane will be less intense than a $23M_V$ star when the HST points within 50 degrees of the sun, 15 degrees of the moon, and 70 degrees of the sunlit earth.

The FGS will detect guide stars of $14m_V$ or brighter. The time from search to detection, for a 30-arcsec radius, is 150 s. In addition, each FGS can calculate the angular position of 10 target stars in the FOV within 10 minutes.

The OTA will operate with an orbital average of 665 W for 27V, with a peak of 803 W as long as the orbital average is within limits.

Solar Arrays. The solar arrays will provide 4000 W or more at 34 V after two years in orbit, even with diode and other loss factors, at the designed temperature. This assumes cell surfaces face the sun within five degrees.

Positioning maneuvers less than 5-5/8 degrees cannot be performed during solar array operation.

D.2 VIEWING/SCHEDULING REQUIREMENTS

The basic viewing requirements are to avoid bright objects, curtail observations above certain noise levels, and communicate via the TDRS system using certain guidelines.

Bright objects, such as the sun or light-reflecting moon and earth, can flood the telescope with stray light and ruin an observation. Requirements are to avoid observations when the sun is within 50 degrees of the aperture opening, or when the moon and earth are within 15 degrees of the aperture. Exceptions may be given special authorization, such as lunar-eclipse observations.

The South Atlantic Anomaly (SAA) is a region of weak terrestrial magnetic field which allows energetic charged particles to reach low altitudes. This could preclude WFPC and FOC observations and calibrations, and FGS operations, when the noise generated by these particles impacting the spacecraft goes beyond a limit calculated by formula. Loss of FGS pointing could also impact other SIs normally oblivious to this radiation noise.

TDRSS scheduling impacts any communication with the STOCC, and atmospheric interference also can affect communications. The earth "limb" can block transmission if the HGA beam is intercepted by the limb. Solar static also can affect communications for the TDRS or ground antennas. No transmission is possible when the TDRS is in earth shadow, or when the HST is within radio-frequency interference.

STScI administration or individual observation needs will dictate other viewing or scheduling requirements.

Appendix E
ORBITAL REPLACEABLE UNITS

Table E-1 lists each Hubble Space Telescope component considered a replaceable unit, the number of each component carried on the HST, and its location on-board.

Table E–1 HST ORUs

Description	No	Location: (Bay) or Other
DF-224 Computer	1	(1, SSM ES)
Battery	6	(2,3, SSM ES)
FGE	3	(D,F,G, OTA ES)
SI C&DH	1	(10, SSM ES)
RWA	4	(6,9, SSM ES)
RSU	3	SSM Shelf
RGE/ECU	3	(10), SSM Shelf
Fuse Plug	12	(4), SSM Shelf
Diode Box	2	Fwd face of SSM ES
SA (Stowed)	2	Along V1, ±V2
RBM (FGS/WFS)	3	In FPSA, ±V2, & + V3 Radial Bay
WF/PC	1	In FPSA, –V3 Radial Bay
HRS	1	In FPSA, Axial Bay 1 (+V2, +V3)
FOS	1	In FPSA, Axial Bay 2 (+V2, –V3)
FOC	1	In FPSA, Axial Bay 3 (–V2, –V3)
HSP	1	In FPSA, Axial Bay 4 (–V2, +V3)
DMU	1	(1, SSM ES)
MAT	2	(5, SSM ES)
SADE	2	(7, SSM ES)
TR	3	(5, 8, SSM ES)
EP/TCE	1	(H), OTA ES
DIU	4	(B), OTA ES
OCE	1	(C), OTA ES
MCU	1	(7, SSM ES)
SAT	2	(5, SSM ES)